(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
30 September 2004 (30.09.2004)

PCT

(10) International Publication Number
WO 2004/083919 A1

(51) International Patent Classification[7]: G02B 6/20

(21) International Application Number: PCT/GB2004/001288

(22) International Filing Date: 22 March 2004 (22.03.2004)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

0306606.5	21 March 2003 (21.03.2003)	GB
0306593.5	21 March 2003 (21.03.2003)	GB
0321991.2	19 September 2003 (19.09.2003)	GB
0322024.1	19 September 2003 (19.09.2003)	GB

(71) Applicant (*for all designated States except US*): **BLAZEPHOTONICS LIMITED** [GB/GB]; Finance Office, University of Bath, The Avenue, Claverton Down, Bath BA2 7AY (GB).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): **BIRKS, Timothy, Adam** [GB/GB]; 14 Horsecombe Brow, Combe Down, Bath BA2 5QY (GB). **RUSSELL, Philip, St. John** [GB/GB]; Shepherds Mead, Southstoke, Bath BA2 7EB (GB). **ROBERTS, Peter, John** [GB/GB]; 11 Gladstone Road, Bath BA2 5HJ (GB). **WILLIAMS, David, Philip** [GB/GB]; Flat 7, 27 Marlborough Buildings, Bath BA1 2LY (GB). **SABERT, Hendrik** [DE/GB]; Flat 2, 19 Royal Crescent, Bath BA1 2LT (GB).

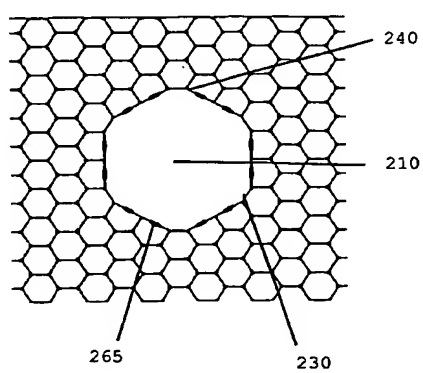
(74) Agents: **CRITTEN, Matthew, Peter** et al.; Abel & Imray, 20 Red Lion Street, London WC1R 4PQ (GB).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW),

[Continued on next page]

(54) Title: PHOTONIC BANDGAP OPTICAL WAVEGUIDE WITH ANTI-RESONANT NODULES AT CORE BOUNDARY



(57) **Abstract:** The present invention relates to improved photonic crystal optical fibres that in preferred embodiments confine light to a core region of the fibre by the action of both a photonic band-gap cladding and an antiresonant core boundary, at the interface between the core and cladding. According to embodiments of the present invention, a fibre has a core (210), comprising an elongate region of relatively low refractive index, a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light including an operating wavelength of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions and a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness that varies around the core to define features (265) that are substantially anti-resonant at the operating wavelength of the fibre.

WO 2004/083919 A1

Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

PHOTONIC BANDGAP OPTICAL WAVEGUIDE WITH ANTI-RESONANT NODULES AT CORE BOUNDARY

This present invention is in the field of optical waveguides and relates in particular, but not exclusively, to optical waveguides that guide light by virtue of a photonic bandgap.

Optical fibre waveguides, which are able to guide light by virtue of a so-called photonic bandgap (PBG), were first proposed in 1995.

In, for example, "Full 2-D photonic bandgaps in silica/air structures", Birks et al., Electronics Letters, 26 October 1995, Vol. 31, No. 22, pp.1941-1942, it was proposed that a PBG may be created in an optical fibre by providing a dielectric cladding structure, which has a refractive index that varies periodically between high and low index regions, and a core defect in the cladding structure in the form of a hollow core. In the proposed cladding structure, periodicity was provided by an array of air holes that extended through a silica glass matrix material to provide a PBG structure through which certain wavelengths of light could not pass. It was proposed that light coupled into the hollow core defect would be unable to escape into the cladding due to the PBG and, thus, the light would remain localised in the core defect.

It was appreciated that light travelling through a hollow core defect, for example filled with air or even under vacuum, would suffer significantly less from undesirable effects, such as non-linearity and loss, compared with light travelling through a solid silica or doped silica fibre core. As such, it was appreciated that a PBG fibre may find application as a transmission fibre to transmit light over extremely long distances, for example across the Atlantic Ocean, without undergoing signal regeneration or as a high optical power delivery waveguide. In contrast, for standard index-guiding,

single mode optical fibre, signal regeneration is typically required approximately every 80 kilometres.

The first PBG fibres that were attempted by the inventors had a periodic cladding structure formed by a triangular lattice of circular air holes embedded in a solid silica matrix and surrounding a central air core defect. Such fibres were formed by stacking circular or hexagonal capillary tubes, incorporating a core defect into the cladding by omitting a central capillary of the stack, and then heating and drawing the stack, in a one or two step process, to form a fibre having the required structure. The first fibres made by this process had a core defect formed by the omission of a single capillary from the centre of the cladding structure.

International patent application PCT/GB00/01249 (The Secretary of State for Defence, UK), filed on 21 March 2000, proposed the first PBG fibre to have a so-called seven-cell core defect, surrounded by a cladding comprising a triangular lattice of air holes embedded in an all-silica matrix. The core defect was formed by omitting an inner capillary and, in addition, the six capillaries surrounding the inner capillary. This fibre structure was seen to guide one or two modes in the core defect, in contrast to the previous, single-cell core defect fibre, which appeared not to support any guided modes in the core defect.

According to PCT/GB00/01249, it appeared that the single-cell core defect fibre, by analogy to the density-of-states calculations in solid-state physics, would only support approximately 0.23 modes. That is, it was not surprising that the single-cell core defect fibre appeared to support no guided modes in its core defect. In contrast, based on the seven-fold increase in core defect area (increasing the core defect radius by a factor of $\sqrt{7}$), the seven-cell core defect fibre was predicted to support approximately 1.61 spatial modes in the core defect. This prediction was consistent with

the finding that the seven-cell core defect fibre did indeed appear to support at least one guided mode in its core defect.

A preferred fibre in PCT/GB00/01249 was described as having a core defect diameter of around 15μm and an air-filling fraction (AFF) - that is, the proportion by volume of air in the cladding - of greater than 15% and, preferably, greater than 30%.

In "Analysis of air-guiding photonic bandgap fibres", Optics Letters, Vol. 25, No. 2, January 15, 2000, Broeng et al. provided a theoretical analysis of PBG fibres. For a fibre with a seven-cell core defect and a cladding comprising a triangular lattice of near-circular holes, providing an AFF of around 70%, the structure was shown to support one or two air guided modes in the core defect. This was in line with the finding in PCT/GB00/01249.

In the chapter entitled "Photonic Crystal Fibers: Effective Index and Band-Gap Guidance" from the book "Photonic Crystal and Light Localization in the 21st Century", C.M. Soukoulis (ed.), ©2001 Kluwer Academic Publishers, the authors presented further analysis of PBG fibres based primarily on a seven-cell core defect fibre. The optical fibre was fabricated by stacking and drawing hexagonal silica capillary tubes. The authors suggested that a core defect must be large enough to support at least one guided mode but that, as in conventional fibres, increasing the core defect size would lead to the appearance of higher order modes. The authors also went on to suggest that there are many parameters that can have a considerable influence on the performance of bandgap fibres: choice of cladding lattice, lattice spacing, index filling fraction, choice of materials, size and shape of core defect, and structural uniformity (both in-plane and along the axis of propagation).

WO 02/075392 (Corning, Inc.) identifies a general relationship in PBG fibres between the number of so-called

surface modes that exist at the boundary between the cladding and core defect of a PBG fibre and the ratio of the radial size of the core defect and a pitch of the cladding structure, where pitch is the centre to centre spacing of nearest neighbour holes in the triangular lattice of the exemplified cladding structure. It is suggested that when the core defect boundary, together with the photonic bandgap crystal pitch, are such that surface modes are excited or supported, a large fraction of the "light power" propagated along the fibre is essentially not located in the core defect. Accordingly, while surface states exist, the suggestion was that the distribution of light power is not effective to realise the benefits associated with the low refractive index core defect of a PBG crystal optical waveguide. The mode energy fraction in the core defect of the PBG fibre was shown to vary with increasing ratio of core defect size to pitch. In other words, it was suggested that the way to increase mode energy fraction in the core defect is by decreasing the number of surface modes, in turn, by selecting an appropriate ratio of the radial size of the core defect and a pitch of the cladding structure. In particular, WO 02/075392 states that, for a circular core structure, a ratio of core radius to pitch of around 1.07 to 1.08 provides a high mode power fraction of not less than 0.9 and is single mode guiding. Other structures are considered, for example in Figure 7, wherein the core defect covers an area equivalent to 16 cladding holes.

The reason why varying the ratio of the radial size of the core defect and a pitch of the cladding structure affects the nature of the surface modes supported by a PBG fibre can be explained with reference to the book "Photonic Crystals: Molding the Flow of Light", Joannopoulos et al., Princeton University Press, ISBN 0-691-03744. The text describes in detail the nature of surface modes and, in particular, the reasons why they form at an interface between a PBG structure

and a defect (or other termination of the PBG structure). In brief, surface modes occur when there are electromagnetic modes near the surface, but they are not permitted to extend into the PBG crystal at the respective frequency due to the PBG. The book goes on to describe that the characteristics, and indeed the presence at all, of the surface modes can be tuned by varying the termination position of the PBG structure. For example, a PBG structure that terminates by cutting through air holes has different surface mode characteristics than the same PBG structure that terminates by cutting through only solid material around holes. WO 02/075392 is consistent with this since varying the core defect size of a PBG fibre naturally varies the termination position of the PBG structure.

In a Post-deadline paper presented at ECOC 2002, "Low Loss (13dB) Air core defect Photonic Bandgap Fibre", N. Venkataraman et al. reported a PBG fibre having a seven-cell core defect that exhibited loss as low as 13dB/km at 1500nm over a fibre length of one hundred metres. The structure of this fibre closely matches the structure considered in the book chapter referenced above. The authors attribute the relatively small loss of the fibre as being due to the high degree of structural uniformity along the length of the fibre.

More recently, the present applicant has presented a post-deadline paper at OFC 2004: "Low loss (1.7 dB/km) hollow core photonic bandgap fiber", Mangan et al. This paper reports the lowest loss result ever achieved by a PBG fibre and goes on to propose that scaling the fibre to operate at a longer wavelength should reduce loss even further. In conventional state-of-the-art solid silica fibers, attenuation is dominated by Rayleigh scattering and multi-phonon absorption at short and long wavelengths, respectively, resulting in an attenuation minimum at around 1550 nm. In hollow-core PBG fibres most of the light does not travel in

glass, and therefore the effects of Rayleigh scattering and multi-phonon absorption in the bulk material are significantly reduced, while the internal surfaces of the fiber become a potentially much more important contributor to loss. Theoretical considerations indicate that the attenuation due to mode coupling and scattering at the internal air/glass interfaces, which dominate the loss in the fiber reported, should scale with the wavelength λ as λ^{-3}. This was confirmed by the empirical data showing the minimum loss of hollow-core PBG fibres designed for various operating wavelengths in a wavelength range where IR absorption is negligible. It is likely that silica hollow-core PBG fibres will achieve their lowest loss somewhere in the 1800-2000 nm wavelength range, well beyond the wavelength at which bulk silica assumes its minimum loss.

An alternative kind of PBG fibre, which does not have a cladding comprising a lattice of high and low refractive index regions, is described in WO00/22466. These PBG fibres typically comprise, in a transverse cross section, concentric, increasingly large, annuli of varying high and low refractive index material, which create an omni-directional reflector capable of confining light to a core region of the fibre.

PBG fibre structures are typically fabricated by first forming a pre-form and then heating and drawing an optical fibre from that pre-form in a fibre-drawing tower. It is known either to form a pre-form by stacking capillaries and fusing the capillaries into the appropriate configuration of pre-form, or to use extrusion.

For example, in PCT/GB00/01249, identified above, a seven-cell core defect pre-form structure was formed by omitting from a stack of capillaries an inner capillary and, in addition, the six capillaries surrounding the inner capillary. The capillaries around the core defect boundary in the stack were supported during formation of the pre-form by

inserting truncated capillaries, which did not meet in the middle of the stack, at both ends of the capillary stack. The stack was then heated in order to fuse the capillaries together into a pre-form suitable for drawing into an optical fibre. Clearly, only the fibre drawn from the central portion of the stack, with the missing inner seven capillaries, was suitable for use as a hollow core defect fibre.

US patent application number US 6,444,133 (Corning, Inc.), describes a technique of forming a PBG fibre pre-form comprising a stack of hexagonal capillaries in which the inner capillary is missing, thus forming a core defect of the eventual PBG fibre structure that has flat inner surfaces. In contrast, the holes in the capillaries are round. US 6,444,133 proposes that, by etching the entire pre-form, the flat surfaces of the core defect dissolve away more quickly than the curved surfaces of the outer capillaries. The effect of etching is that the edges of the capillaries that are next to the void fully dissolve, while the remaining capillaries simply experience an increase in hole-diameter. Overall, the resulting pre-form has a greater fraction of air in the cladding structure and a core defect that is closer to a seven-cell core defect than a single cell core defect.

PCT patent application number WO 02/084347 (Corning, Inc.) describes a method of making a pre-form comprising a stack of hexagonal capillaries of which the inner capillaries are preferentially etched by exposure to an etching agent. Each capillary has a hexagonal outer boundary and a circular inner boundary. The result of the etching step is that the centres of the edges of the hexagonal capillaries around the central region dissolve more quickly than the corners, thereby causing formation of a core defect. In some embodiments, the circular holes are offset in the inner hexagonal capillaries of the stack so that each capillary has a wall that is thinner than its opposite wall. These capillaries are arranged in the

stack so that their thinner walls point towards the centre of the structure. An etching step, in effect, preferentially etches the thinner walls first, thereby forming a seven-cell core defect.

An object of the present invention is to provide a PBG waveguide having improved properties, in particular lower loss, than prior art PBG waveguides.

In arriving at the present invention, the inventors have demonstrated that, while the size of a core defect is significant in determining certain characteristics of a PBG waveguide, the form of a boundary at the interface between core and cladding also plays a significant role in determining certain characteristics of the waveguide. As will be described in detail hereafter, the inventors have determined that, for given PBG core and cladding structures, variations in only the form of the boundary can cause significant changes in the characteristics of a respective waveguide.

According to the invention there is provided an elongate waveguide for guiding light comprising:

a core, comprising an elongate region of relatively low refractive index; and

a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core;

characterised in that the boundary region has a shape such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 95% of the guided light is in the regions of relatively low refractive index in the waveguide.

In referring to the 'shape' of the boundary region, we mean 'shape' in a broad sense, both its gross shape (whether it is for example circular or hexagonal or dodecagonal or some other shape) and fine details of its shape, for example the presence or absence of local variations in thickness (for example, nodes or nodules) around its perimeter. (It is expected that the gross shape of the boundary will generally define the shape of the core.) We also use the word 'shape' to encompass the size of the boundary region; for example, we regard a boundary region that is a circular shell in the transverse plane to have a different shape for a different diameter of the shell or for a different thickness of the shell, even though it remains a circular shell in each of those cases.

The regions of relatively low refractive index in the waveguide of course comprise the regions of relatively low refractive index in the photonic bandgap structure and the region of relatively low refractive index in the core.

The regions of relatively low refractive index may have a refractive index of less than 2, less than 1.8, less than 1.6, less than 1.5, less than the refractive index of silica, less than 1.4, less than 1.3, less than the refractive index of typical polymer glasses (for example, less than 1.25), less than 1.2 or even less than 1.1 or even less than 1.05, or be 1 for the case of a vacuum.

The inventors have discovered that in considering how best to lower loss in an optical waveguide having a photonic bandgap cladding structure, it is helpful to consider the behaviour of distinct features in the cladding boundary as being that of optical resonators.

Considering, for example, an air-core and silica PBG fibre, the inventors have determined that the geometry of the region of the boundary between the air core and the photonic bandgap cladding structure has profound effects on the modal

properties of the fibre. In particular, the inventors have appreciated that the number of guiding modes within the band gap, the fraction of the light power of the guided modes confined within the air core and the field intensity of these modes at the air-silica interfaces all vary sensitively with the geometry within the region. In particular, the inventors have shown that by tailoring the geometry, the properties of an LP_{01}-like mode (when present), which possesses an approximately Gaussian intensity profile towards the centre of the core, can be tailored so that up to and even over 99% of the light is confined within air, and predominantly in the core. This implies that loss due to Rayleigh scattering in the silica may be suppressed by up to two orders of magnitude and that nonlinearity may be substantially reduced compared with standard index guiding single mode fibre. Also, the inventors have demonstrated that the core boundary geometry can be designed to reduce the field intensity of this mode strongly in the vicinity of the air-silica interfaces. This has the effect of reducing both the small scale interface roughness scattering, which is discussed in detail hereafter, and the mode coupling due to longer range fibre variations.

The inventors have determined that the design of a core-cladding interface, or boundary region, can exploit an anti-resonance effect to strongly enhance the power in air fraction, η, and reduce the field intensity at the air-silica interfaces of core-guided modes, such as the LP_{01}-like mode. Antiresonant boundaries have also been found, in at least some embodiments, to have the benefit of reducing the effects of, or even removing, so-called surface modes that can exist at a core boundary and potentially interfere with the core-guided modes. This is particularly surprising given that an antiresonant core boundary does not typically match the form of the cladding.

A simple example of an optical resonator is the Fabry-Perot interferometer. Whether or not light can resonate in such a feature depends on the feature's size, shape and composition, and also on the wavelength and direction of propagation of the light. As the wavelength is varied the feature moves into and out of resonance.

Such antiresonant effects can be observed in slab-like resonators, having plane parallel faces between which light is reflected and interferes destructively at antiresonance. The effect can also be observed in a ring-like resonator, where interference is between reflectors from an outer and an inner shell surface. It has been reported by Litchinitser *et al.*, Opt. Lett., Vol. 27 (2002) pp. 1592-1594, that light may be guided in a PBG-like fibre predominantly by anti-resonant reflection in multiple cladding layers. Litchinitser *et al.* describe a fibre structure comprising a low index core surrounded by plural concentric layers of high and low index material, the relative thickness of which were chosen to provide an anti-resonant cladding structure for confining light to the core region.

Litchinitser also mentions a PCF consisting of a silica core surrounded by holes filled with high index liquid. In that case the silica represents the low index medium and the filled holes are the features that act as resonators. At their antiresonant wavelengths, the filled holes substantially exclude light and thus confine light to the relatively low-index silica core. The present inventors have considered more complicated structures, which may, for example, comprise high-index features interconnected by high index "struts", whereas the resonators described by Litchinitser *et al.* are isolated cylinders. Nevertheless the present inventors have discovered that such interconnected features can act as distinct resonators, and serve to confine light in the low index medium (for example, air) when they are antiresonant.

For a given excitation, on resonance, the optical power in the features assumes a maximum. In between resonances, optical power in the features is minimised. In a photonic crystal fibre, if the relatively low refractive index regions are air, it is desirable to maximise the amount of light in these regions in order to reduce scattering, non-linearities and other deleterious effects. Hence it is advantageous to incorporate features that possess strong distinct resonances, and adjust their sizes and shapes so that they are antiresonant at the optical wavelengths and directions of propagation of interest.

That is advantageous as it raises the proportion of light in low-index regions and decreases F-factor (defined below), which is a measure of the amount of light at glass/air interfaces.

The present inventors have discovered that confinement of light to a core of a PBG fibre, which confines light to the core region by virtue of a photonic bandgap, may be enhanced by providing, at the interface between the core and the photonic bandgap cladding, a boundary which is tuned to be substantially anti-resonant. Unlike in Litchinitser et al., in which antiresonance is achieved using concentric layers of material or distinct, unconnected resonators, a core boundary proposed herein may comprise plural anti-resonant features around an unbroken, but otherwise generally non-antiresonant, core boundary. The present inventors have discovered that such a core boundary can be arranged to be antiresonant at an operating wavelength, and thereby serve to confine light to the core of the waveguide. The present inventors have also discovered that it is possible to achieve a similar confinement of light to a core by arranging a single, unbroken region of relatively high refractive index at the interface between the core and the photonic bandgap structure. This latter kind of confinement, while being closely related to the

former kind, is described more fully in applicant's co-pending International Patent Application, having the title "Enhanced Optical Waveguide", filed on the same date and having the same earliest priority date as this application (the entire contents of the co-pending application is hereby incorporated herein by reference).

As discussed above, guiding light in a region of relatively low refractive index has the advantage that losses, nonlinear effects and other material effects are generally lower in such regions, particularly if the region is a region of air or a gas. Thus preferably, ever more of the light is guided in the regions of relatively low refractive index in the PBG structure or in the region of relatively low refractive index in the core: preferably more than 96%, more than 97%, more than 98%, more than 99%, more than 99.3%, more than 99.5% or even more than 99.9% of the light is in those regions.

The boundary region may have a shape such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 50% of the guided light is in the region of relatively low refractive index in the core. It is significant that the inventors have recognised that the light need not be in the core region for beneficial effects to be achieved. Thus, the boundary region may have a shape such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 1% of the guided light is in the regions of relatively low refractive index in the photonic bandgap structure. It may be that still more of the guided light is in those regions in the PBG structure: more than 2%, more than 5% or even more than 10% of the light may be in those regions.

F-factor has been identified by the present inventors as a useful figure of merit which relates to how the guided light

propagating in a PBG fibre is subject to scattering from small scale irregularities of the air-silica interfaces. F-factor is also believed to be a strong indicator of likely mode-coupling characteristics of a PBG-fibre.

The guided light propagating in a PBG waveguide is subject to scattering from small scale irregularities of the interfaces between higher refractive index regions and lower refractive index regions. That loss mechanism acts in addition to the Rayleigh scattering due to index inhomogeneity within the higher index regions. The latter loss mechanism is strongly suppressed in PBG waveguides having for example an air core, since most of the light power resides in air. The amount of scattering associated with the interfaces can be minimised by ensuring that impurities are eliminated during the draw process; such impurities can act as scattering (and absorption) centres directly, and can operate as nucleation sites for crystallite formation. With such imperfections removed, there still remains interface roughness governed by the thermodynamics of the drawing process. Such fluctuations are likely to be difficult or impossible to remove.

The Rayleigh scattering due to small scale roughness at the lower-index/higher-index (e.g. air-silica) interfaces can be calculated by applying a perturbation calculation. The analysis has a simple interpretation in terms of effective particulate scatterers distributed on the interfaces. If the root-mean square (RMS) height roughness is h_{rms} and the correlation lengths of the roughness along the hole direction and around the hole perimeter are L_z and L_ϕ respectively, then a typical scatterer has a volume $h_{rms}L_zL_\phi$. The induced dipole moment of the typical scatterer is then given by

$$\mathbf{p} = \Delta\varepsilon \mathbf{E}_0 h_{rms} L_z L_\phi , \quad (1)$$

where $\Delta\varepsilon$ is the difference in dielectric constant between the higher-index and the lower-index regions, and $\mathbf{E}_0$ is the E-field

strength at the scatterer. That induced dipole moment radiates a power, in the free space approximation, given by

$$P_{sc} = \frac{1}{12\pi}\left(\frac{\omega}{c}\right)^4\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2}|\mathbf{p}|^2 = \frac{1}{12\pi}\left(\frac{\omega}{c}\right)^4 \Delta\varepsilon^2 h_{rms}^2 L_z^2 L_\phi^2 \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} |\mathbf{E}_0|^2 . \qquad (2)$$

The number density of particles on the interface will be $\sim 1/(L_z L_\phi)$ so that the total radiated power from a section of length L of the perturbed fibre will be approximately

$$P_{rad} \sim \frac{1}{12\pi}\left(\frac{\omega}{c}\right)^4 \Delta\varepsilon^2 h_{rms}^2 L_z L_\phi L \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \oint_{\substack{\text{hole}\\\text{perimeters}}} \mathrm{d}s |\mathbf{E}_0|^2 \qquad (3)$$

The loss rate is thus given by

$$\gamma = \frac{P_{rad}}{P_0 L} \sim \frac{1}{6\pi}\left(\frac{\omega}{c}\right)^4 \Delta\varepsilon^2 h_{rms}^2 L_z L_\phi \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{\oint_{\substack{\text{hole}\\\text{perimeters}}} \mathrm{d}s |\mathbf{E}_0|^2}{\int \mathrm{d}S (\mathbf{E}_0 \wedge \mathbf{H}_0^*) \cdot \hat{\mathbf{z}}} \qquad (4)$$

where the incident power P_0 has been expressed as a Poynting flux.

Equation (4) shows that the mode shape dependence of the Rayleigh interface roughness scattering strength is governed by a factor F given by

$$F = \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{\oint_{\substack{\text{hole}\\\text{perimeters}}} \mathrm{d}s |\mathbf{E}_0(\mathbf{r}')|^2}{\int_{\text{x-section}} \mathrm{d}S (\mathbf{E}_0 \wedge \mathbf{H}_0^*) \cdot \hat{\mathbf{z}}} . \qquad (5)$$

A comparison of the interface scattering strength from guided modes of different fibres with similar interface roughness properties can be based purely on this factor. Indeed, the thermodynamic limit to surface roughness is not expected to vary significantly with the details of the fibre geometry, so that the factor F can be used directly as a figure of merit.

A more rigorous calculation of small scale interface roughness can be derived which takes into account the details on the surface roughness spectrum and deviations from the free space approximation. The latter effect is embodied by a local density of states (LDOS) correction factor appearing in the

integrand of the numerator integral in equation (5). Ideally, to minimise the interface loss, the field intensity of the guiding mode multiplied by the LDOS factor should be maintained as small as possible at the interfaces. In practise, the LDOS correction is found to be small even for (silica/air) band gap fibres in comparison with the guided mode field intensity factor, so that the factor F given in expression (5) may be used to compare the interface scattering strength from guided modes of different fibre designs.

The effect of the scattering from crystallites which have formed close to the air/silica interfaces can be calculated in a similar way to the geometrical roughness considered above. Assuming the number density per unit interface length and the size of the crystallites is independent of fibre design, again F can be used directly to compare the interface scattering strengths.

The boundary region may have a shape such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than 0.23 μm^{-1}. That figure is calculated assuming that the waveguide guides light at a frequency of 1.55 µm. For the case in which the Photonic Band Gap structure is a periodic structure having a pitch Λ, the F-factor is preferably less than 0.7 Λ^{-1}.

Also according to the invention there is provided an elongate waveguide for guiding light comprising:

a core, comprising an elongate region of relatively low refractive index; and

a photonic bandgap structure arranged to provide a photonic bandgap over a range of frequencies of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core;

characterised in that the boundary region has a shape such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than 0.23 μm^{-1} (or, for a waveguide in which the Photonic Band Gap structure is a periodic structure having a pitch Λ, $0.7\Lambda^{-1}$).

Preferably, still lower F-factors are provided: less than 0.192 μm^{-1} (or $0.6\Lambda^{-1}$ if periodic), less than 0.16 μm^{-1} (or $0.5\Lambda^{-1}$ if periodic), less than 0.128 μm^{-1} (or $0.4\Lambda^{-1}$ if periodic), less than 0.10 μm^{-1} (or $0.3\Lambda^{-1}$ if periodic), less than 0.080 μm^{-1} (or $0.25\Lambda^{-1}$ if periodic), less than 0.065 μm^{-1} (or $0.2\Lambda^{-1}$ if periodic), less than 0.060 μm^{-1} (or $0.188\Lambda^{-1}$ if periodic), less than 0.055 μm^{-1} (or $0.17\Lambda^{-1}$ if periodic), less than 0.052 μm^{-1} (or $0.163\Lambda^{-1}$ if periodic), less than 0.048 μm^{-1} (or $0.15\Lambda^{-1}$ if periodic), less than 0.04 μm^{-1} (or $0.125\Lambda^{-1}$ if periodic), less than 0.032 μm^{-1} (or $0.10\Lambda^{-1}$ if periodic), less than 0.029 μm^{-1} (or $0.090\Lambda^{-1}$ if periodic), less than 0.026 μm^{-1} (or $0.080\Lambda^{-1}$ if periodic), less than 0.022 μm^{-1} (or $0.070\Lambda^{-1}$ if periodic), less than 0.02 μm^{-1} (or $0.063\Lambda^{-1}$ if periodic), less than 0.019 μm^{-1} (or $0.060\Lambda^{-1}$ if periodic), less than 0.016 μm^{-1} (or $0.05\Lambda^{-1}$ if periodic), less than 0.013 μm^{-1} (or $0.040\Lambda^{-1}$ if periodic), less than 0.012 μm (or $0.038\Lambda^{-1}$ if periodic), 0.010 μm^{-1} (or $0.030\Lambda^{-1}$ if periodic), less than 0.006 μm^{-1} (or $0.020\Lambda^{-1}$ if periodic), or even less than 0.003 μm^{-1} (or $0.010\Lambda^{-1}$ if periodic) are preferred.

The relevant F-factor is typically the F-factor only of the mode of interest (for example, the fundamental mode, ignoring higher-order modes).

The features next discussed may be found in embodiments of either aspect of the invention (relating to high levels of light in the relatively low refractive index regions or relating to F-factor).

In the transverse cross section, the photonic bandgap structure may comprise an array of the relatively low refractive index regions separated from one another by the

relatively high refractive index regions. The array may be substantially periodic. (However, in principle, the array need not be periodic - see, for example, the paper by N. M. Litchinitser et al. discussed above. Although that paper does not provide calculations explicitly for PBG fibres, it does illustrate that photonic bandgaps may be obtained without periodicity.)

It is highly unlikely in practice that a photonic bandgap structure according to the present invention will comprise a 'perfectly' periodic array, due to imperfections being introduced into the structure during its manufacture and/or perturbations being introduced into the array by virtue of the presence of the core defect. The present invention is intended to encompass both perfect and imperfect structures. Likewise, any reference to "periodic", "lattice", or the like herein, imports the likelihood of imperfection.

The array may be a substantially triangular array. Other arrays, of course, may be used, for example, square, hexagonal or Kagome, to name just three.

The array may have a characteristic primitive unit cell and a pitch Λ.

The boundary region may comprise, in the transverse cross-section, a plurality of relatively high refractive index boundary veins joined end-to-end around the boundary between boundary nodes, each boundary vein being joined between a leading boundary node and a following boundary node, and each boundary node being joined between two boundary veins and to a relatively high refractive index region of the photonic bandgap structure. Thus, a vein sits between two nodes, with no other node between the two nodes; i.e., it sits between two neighbouring nodes.

At least one of the boundary veins may comprise, along its length or at its end, a nodule. The nodule may have a substantially elliptical shape in the transverse cross-

section, such that an ellipse having a major axis of length L and a minor axis of length W substantially fits to the shape of the nodule. The major axis may extend along the boundary vein in which the nodule is situated.

The waveguide may guide light at a wavelength λ_1, which may be any wavelength at which the waveguide is substantially transparent. The wavelength λ_1 may be in the ultraviolet, visible or infrared parts of the electromagnetic spectrum. The wavelength λ_1 may be in a telecoms window, for example λ_1 may be in the range 1510 nm to 1610 nm or in the 1300 nm band. Alternatively, the wavelength λ_1 may be in the 1060 nm band or in the 810 nm band. Operation may be at a longer wavelength, for example in the range 1.8 to 2.0 μm or in the range 2 μm to 5 μm, at or around the wavelength of operation of CO_2 lasers (10.6 μm).

The waveguide may be arranged to guide light at a wavelength λ_2, wherein light guided at the wavelength λ_2 exhibits lower loss than light guided in the waveguide at any other wavelength.

The lengths of the minor and major axes of an elliptical nodule on a boundary vein have been found to be significant in increasing the fraction of light in the regions of low refractive index and in decreasing the F-factor. In particular it has been found that, in a plane having orthogonal axes along which values of W and L are plotted, particular regions comprise particular pairs of values of W and L (represented by co-ordinates (L,W) in the plane) that provide a higher fraction of light in the regions of low refractive index, or a lower F-factor, than is found in prior-art waveguides. Table 1 sets out relations between W and L that conveniently define those particular regions. Various regions of interest may be defined more precisely by taking combinations of two or more of those relations.

Some of the relations are defined in terms of a parameter X, which is used for brevity, to reduce the number of claims necessary to cover envisaged possibilities. Thus, parameter X may be equal to the wavelength λ_1 or the wavelength λ_2 or, where the waveguide has a pitch Λ as described above, the pitch Λ.

Table 1: Relations defining preferred regions of the L-W plane

(N.B. The relations are set out in two columns purely for conciseness; the relations in adjacent columns are as independent of each other as are all other relations in the table).

$W \approx L$	$L \times W \approx \frac{X^2}{12}$
$W \leq 0.467L$	$L \times W \leq 0.113X^2$
$W \approx \frac{L}{3}$	$W \leq \left(\frac{1}{18} + \frac{L}{3}\right)X$
$W \geq 0.238L$	$W \geq \left(-\frac{1}{18} + \frac{L}{3}\right)X$
$L \geq \frac{5X}{12}$	$W \geq \left(\frac{5}{18} - \frac{L}{3}\right)X$
$L \approx \frac{X}{2}$	$W \leq \left(\frac{7}{18} - \frac{L}{3}\right)X$
$L \leq \frac{7X}{12}$	$W \geq (-0.133 + 0.467L)X$
$W > \frac{X}{18}$	$W \leq (0.095 + 0.238L)X$
$W > \frac{5X}{36}$	$W \geq (0.333 - 0.467L)X$
$W \approx \frac{X}{6}$	$W \leq (0.333 - 0.238L)X$
$W \leq \frac{7X}{36}$	$W \leq (0.467 - 0.467L)X$
$L \times W \geq 0.058X^2$	$W \leq (0.238 - 0.238L)X$

$L < 0.27\Lambda$	$W < 0.11\Lambda$
$L > 0.45\Lambda$	$W > 0.21\Lambda$

The F-factor of a structure may be improved by increasing the size of the core. The core may have, in the transverse cross-section, an area that is significantly greater than the area of at least some of the relatively low refractive index regions of the photonic bandgap structure. The core may have, in the transverse cross-section, an area that is greater than twice the area of at least some of the relatively low refractive index regions of the photonic bandgap structure.

The core may have, in the transverse cross-section, an area that is greater than the area of each of the relatively low refractive index regions of the photonic bandgap structure.

The core may have, in the transverse cross-section, a transverse dimension that is greater than the pitch Λ.

The core may correspond to the omission of a plurality of unit cells of the photonic band-gap structure, for example, the core may correspond to the omission of three, four, six, seven, ten, twelve, nineteen or thirty seven unit cells of the photonic band-gap structure. The core may correspond to the omission of more than thirty seven unit cells of the photonic band-gap structure.

At least some of the relatively low refractive index regions may be voids filled with air or under vacuum.

At least some of the relatively low refractive index regions may be voids filled with a liquid or a gas other than air. The region of relatively low refractive index that makes up the core may comprise the same or a different material compared with the regions of relatively low refractive index in the photonic bandgap structure.

In some embodiments, at least some of the relatively high refractive index regions comprise silica glass. The glass may

be un-doped or doped with index raising or lowering dopants. As used herein 'silica' encompasses fused silica, including doped fused silica, and silicate glasses in general such as germano-silicates and boro-silicates.

In alternative embodiments of the invention the relatively high refractive index regions comprise a material other than silica. For example, it may be an inorganic glass in which multi-phonon absorption only becomes significant at wavelengths significantly longer than for silica. Exemplary inorganic glasses may be in the category of halide glasses, such as a fluoride glass, for example ZBLAN. Alternatively, the relatively high refractive index may comprise another solid material, for example an organic polymer.

The relatively low refractive index regions may make up more than 58% by volume of the photonic bandgap structure. The relatively low refractive index regions may make up more than 60%, more than 64%, more than 65%, more than 70%, more than 75%, more than 80%, more than 85%, more than 90%, more than 91%, more than 92%, more than 93%, more than 94%, or even more than 95%. The relatively low refractive index regions may make around 87.5% by volume of the photonic bandgap structure.

The waveguide may support a mode having a mode profile that closely resembles the fundamental mode of a standard optical fibre. An advantage of this is that the mode may readily couple into standard, single mode optical fibre.

Alternatively, or in addition, the waveguide may support a non-degenerate mode. This mode may resemble a TE_{01} mode in standard optical fibres.

Preferably, in either case, said mode supports a maximum amount of the mode power in relatively low refractive index regions compared with other modes that are supported by the waveguide.

At least some of the boundary veins may be substantially straight. In some embodiments, substantially all of the boundary veins are substantially straight. Alternatively, or additionally, at least some of the boundary veins may be bowed outwardly from, or inwardly towards, the core defect.

At least two of the higher index regions in the photonic bandgap structure may be connected to each other.

The higher index regions in the photonic bandgap structure may be interconnected.

Also according to the invention there is provided an optical fibre comprising a waveguide of a type described above as being according to the invention.

Also according to the invention there is provided a transmission line for carrying data between a transmitter and a receiver, the transmission line including along at least part of its length such a fibre.

Also according to the invention there is provided data conditioned by having been transmitted through such a waveguide. As in any transmission system, data that is carried by the system acquires a characteristic 'signature' determined by a transfer function of the system. By characterising the system transfer function sufficiently accurately, using known techniques, it is possible to match a model of the input data, operated on by the transfer function, with real data that is output (or received) from the transmission system.

Also according to the invention there is provided a method of forming elongate waveguide, comprising the steps:

forming a preform stack by stacking a plurality of elongate elements;

omitting, or substantially removing at least one elongate element from an inner region of the stack; and

heating and drawing the stack, in one or more steps, into a waveguide of a type described above as being according to the invention.

Also according to the invention there is provided a method of forming elongate waveguide for guiding light, comprising the steps:

(a) simulating the waveguide in a computer model, the waveguide comprising a core, comprising an elongate region of relatively low refractive index and a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core, wherein properties of the boundary region are represented in the computer model by parameters;

(b) finding a set of values of the parameters that, according to the model, increases or maximises how much of the light guided by the waveguide is in the regions of relatively low refractive index in the waveguide.

Also according to the invention, there is provided a method of forming elongate waveguide for guiding light, comprising the steps:

(a) simulating the waveguide in a computer model, the waveguide comprising a core, comprising an elongate region of relatively low refractive index, and a photonic bandgap structure arranged to provide a photonic bandgap over a range of frequencies of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the

waveguide, the core, wherein properties of the boundary region are represented in the computer model by parameters;

(b) finding a set of values of the parameters that, according to the model, decreases or minimises the F-factor of the waveguide.

The boundary region may comprise, in the transverse cross-section, a plurality of relatively high refractive index boundary veins joined end-to-end around the boundary between boundary nodes, each boundary vein being joined between a leading boundary node and a following boundary node, and each boundary node being joined between two boundary veins and to a relatively high refractive index region of the photonic bandgap structure and at least one of the boundary veins comprising, along its length, a nodule, the nodule having a substantially elliptical shape in the transverse cross-section, such that an ellipse having a major axis of length L and a minor axis of length W substantially fits to the shape of the nodule in the transverse cross-section. The parameters for which values are found may comprise L and W.

Also according to the invention there is provided an elongate waveguide for guiding light comprising:

a core, comprising an elongate region of relatively low refractive index; and

an outer structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region comprising a continuous shell of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core;

characterised in that the boundary region comprises a feature or has a shape that is antiresonant at a wavelength of light guided in the waveguide.

The boundary region is a continuous shell of relatively high refractive index in that it does not comprise regions of

relatively low refractive index: all relatively-high-index regions in the boundary are connected to each other only by relatively-high-index regions. The core is taken to be contiguous with the boundary region. The core thus comprises all connected regions of relatively low refractive index that are surrounded by the boundary region. The boundary region may be not smooth: it may for example be corrugated, with indented regions (for example, formed by omitting every other vein from an innermost polygon of the cladding, such as what would, if all veins were present, be an hexagon defining an hexagonal core), or it may have one two or more struts that project towards the centre of the core (which struts may be of uniform thickness or may have nodules at some point along their length, for example at their ends). Thus, the core need not be of a regular cross section but may, for example, have projections and indentations defined by the boundary region.

Thus the boundary region may be corrugated with 2, 3, 4, 5, 6, 7, 8, 9, 10 or more recesses or indentations, which may be arranged at regular intervals around the centre of the core.

The outer structure may exhibit a photonic band-gap. Even if the outer structure is not a photonic bandgap structure, any features set out above in relation to other aspects of the invention having a bandgap structure may be found in the present further aspect of the invention unless that is not physically meaningful.

The boundary region may have a different structure from the structure of the rest of the outer structure. For example, the regions of relatively high refractive index in the boundary region may be thicker or thinner than corresponding regions in the rest of the outer structure. The regions of relatively high refractive index may include nodes or nodules that are in different positions or have different sizes from corresponding features in the rest of the outer

structure (it may be that there are no corresponding features in the outer structure or that there are such features in the outer structure but they are not present in the boundary region). The regions of relatively high refractive index in the boundary region may include a region of a different refractive index from the refractive index of corresponding region in the outer structure.

The boundary region may comprise a nodule. The boundary region may comprise 2, 3, 4, 5, 6, 7, 8, 9, 12 or more nodules, which may be arranged at regular intervals around the centre of the core. The nodules may be arranged at the centres of veins, where each vein extends between two nodes.

Alternatively, the nodules may be arranged off-centre on such a vein. The nodules may be arranged such that the waveguide has in cross-section no more than two-fold rotational symmetry. The waveguide may then be birefringent.

The outer structure may comprise a periodic array of unit cells. The core may be of a size larger than one such unit cell, larger than 7 such unit cells (which corresponds to a central cell and six surrounding cells in a hexagonal arrangement) or even larger than 19 such unit cells (which corresponds to a central cell and two rings of surrounding cells in a hexagonal arrangement). The waveguide may comprise a jacket around the outer structure.

It may be that the boundary region comprises more or fewer than six nodules.

Also according to the invention there is provided a photonic crystal fibre comprising:

an outer structure comprising a periodic array of unit cells, each unit cell comprising a central region of a vacuum or a fluid and an outer region of a solid material, the periodic array having a pitch Λ; and

a core, comprising an elongate region of a vacuum or a fluid;

the outer structure including a boundary region comprising a plurality of veins of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core;

characterised in that the veins include nodules that are antiresonant at a wavelength of light guided in the waveguide.

The unit cells may be hexagonal. The central region of the unit cell may be air. The central region of the unit cell may be circular with a diameter d. The nodules may be elliptical in cross-section. The ellipse may have a major axis of length 5Λ/12. The ellipse may have a minor axis of length Λ/6. The core may have the same size and shape as a group of seven unit cells of the outer structure. The waveguide may guide light in the C-band telecoms window, around 1550 nm (1530 nm to 1570 nm). The waveguide may guide light having a wavelength in the range 3µm to 5µm. The vacuum or fluid may fill the outer structure to a filling fraction of about 92%. The ratio d/Λ may be about 0.97. The pitch Λ may be about 3µm. The diameter of the core may be about 9µm. The unit cell central region diameter may be about 2.9. The veins may be of substantially constant thickness over about half their length. If the pitch Λ is 3µm when the waveguide is designed to operate at 1550 nm, then pitches may be found that are suitable for operation at other wavelengths in similar waveguide structures by scaling the pitch Λ in proportion to the wavelength, i.e., a corresponding pitch for light of 3 µm would be 6 µm, if the filling fraction of the vacuum or fluid and the ratio d/Λ remain constant and the refraction index is essentially unaltered.

Any of the features described above are applicable interchangeably to any of the above-described aspects of the invention (except where that is nonsensical).

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figure 1 is a diagram of a transverse cross section of a PBG fibre structure according to an embodiment of the invention;

Figure 2 is a schematic diagram of some examples of corral systems comprising dielectric cylinders in air (the dashed lines are used for geometric construction purposes);

Figure 3 is a plot showing the imaginary part of the effective mode index n_{eff} for a corral system comprising six identical silica cylinders in air arranged hexagonally; the distance between the cylinders is Λ=3.0, 4.5 and 6.0µm and the wavelength is λ=1.55µm; Im[n_{eff}], which is plotted against cylinder diameter d, is related to Im[β] by $\mathrm{Im}[n_{eff}]=\frac{\lambda\,\mathrm{Im}[\beta]}{2\pi}$; also shown is Im[β] for a dielectric ring of diameter R=4.5µm vs. its thickness d;

Figure 4 is a plot showing intensity profiles for two corral arrangements of silica cylinders at anti-resonance; the circles show the positions of the cylinder interfaces; the appearance of near nulls close to each cylinder interface is clear; the wavelength was chosen to be λ=1.55µm;

Figure 5 is a plot of the imaginary part of the effective mode index n_{eff} for a corral system comprising 12 identical silica cylinders in air arranged as in the two examples shown in Figure 4, plotted as a function of the cylinder diameter d and an operating wavelength of λ=1.55µm;

Figure 6 is a diagram that illustrates how an ellipse is fitted to nodules in the structure of Figure 1;

Figure 7 is a diagram that illustrates how various physical characteristics of PBG fibres are defined herein;

Figure 8 is a plot of fraction of light in air for a fibre according to an embodiment of the invention, the plot

having axes showing lengths of the major axis L and the minor axis W of the ellipse of Figure 7;

Figure 9 is a plot of F-factor for a fibre according to an embodiment of the invention, the plot having axes showing lengths of the major axis L and the minor axis W of the ellipse of Figure 3;

Figures 10(a) and (b) show various regions of interest in the L-W plane of Figures 8 and 9;

Figure 11 is a diagram of a transverse cross section of a second PBG fibre structure according to an embodiment of the invention;

Figure 12 is a plot of (i) field intensity (linear plot), (ii) azimuthally averaged field intensity (log. plot) and (iii) distribution of F-factor (linear plot) for ((a) and (b)) two orthogonal polarisation modes supported by the fibre of Figure 11;

Figure 13 is a diagram of a transverse cross section of a third PBG fibre structure according to an embodiment of the invention;

Figure 14 is a diagram of a transverse cross section of a fourth PBG fibre structure according to an embodiment of the invention;

Figure 15 is a diagram of a transverse cross section of a fifth PBG fibre structure according to an embodiment of the invention;

Figure 16 is a diagram of a transverse cross section of a sixth PBG fibre structure according to an embodiment of the invention;

Figure 17 is a diagram of a pre-form suitable for making PBG fibre according to embodiments of the present invention;

Figure 18 is a diagram of another pre-form suitable for making a fibre according to embodiments of the present invention;

Figures 19a and 19b are further pre-forms suitable for making fibres according to embodiments of the present invention;

Figure 20a is a microscope photograph of a glass rod attached to the inner periphery of a large diameter capillary, ready to be incorporated into a PBG fibre pre-form, suitable for forming an antiresonant bead in a PBG fibre structure and Figure 20b is a scanning electron microscope image of such a bead in a PBG fibre;

Figure 21a is a microscope photograph of a glass rod attached to the outer periphery of a core boundary in a PBG fibre preform, suitable for forming an antiresonant bead in a PBG fibre structure and Figure 21b is a scanning electron microscope image of such a bead in a PBG fibre; and

Figure 22 is a diagram of a transmission system incorporating a PBG fibre according to the invention.

Figure 1 is a representation of a transverse cross-section of a fibre waveguide structure. In the Figure, the black regions represent fused silica glass and the white regions represent air holes in the glass. As illustrated, the cladding 100 comprises a triangular array of generally hexagonal cells 105, surrounding a seven-cell core defect 110. A core defect boundary 145 is at the interface between the cladding and the core defect. The core defect boundary has twelve sides - alternating between six relatively longer sides 140 and six relatively shorter sides 130 - and is formed by omitting or removing seven central cells; an inner cell and the six cells that surround the inner cell. The cells would have typically been removed or omitted from a pre-form prior to drawing the pre-form into the fibre. As the skilled person will appreciate, although a cell comprises a void, or a hole, for example filled with air or under vacuum, the voids or holes may alternatively be filled with a gas or a liquid or may instead comprise a solid material that has a different

refractive index than the material that surrounds the hole. Equally, the silica glass may be doped or replaced by a different glass or other suitable material such as a polymer. For the sake of simplicity of description herein, however, the following exemplary embodiments are silica and air fibres.

This region of the cladding, although not shown in its entirety, typically extends outwardly to provide a specified degree of light confinement; where more cladding layers provide increased confinement. Typically, although not shown, there are further cladding layers surrounding the photonic band-gap structure. There may be an additional solid silica layer to provide strength and a coating layer to protect the silica and prevent light entering the fibre from the side, as in a normal fibre.

The waveguide of Figure 1 has a substantially periodic structure comprising a triangular lattice of generally hexagonal holes. However, as discussed above, N. M. Litchinitser et al. have demonstrated that photonic bandgaps may be achieved in non-periodic structures. The properties of the core-cladding boundary are also important in non-periodic PBG structures and the invention is not limited to substantially periodic structures but encompasses structures with some or even a high degree of aperiodicity or irregularity in the cladding structure. However, the exemplary embodiments illustrated hereafter use a triangular lattice of the kind shown in Figure 1, which will be familiar to the skilled artisan, in order not to obscure the present invention.

Hereafter, and with reference to Figure 1, a region of glass 115 between any two holes is referred to as a "**vein**" and a region of glass 120 where at least three veins meet is referred to as a "**node**".

A vein can be generally characterised by its transverse, cross-sectional length and thickness at a midpoint between the

two nodes to which it is attached. Veins tend to increase in thickness from their midpoint to the nodes, although a region of substantially constant thickness at the middle of the vein tends to appear and then increase in length with increasing air-filling fraction. Nodes can be generally characterised by a transverse cross-sectional diameter, which is the diameter of the largest inscribed circle that can fit within the node. In the fibre structures investigated herein, node diameter is typically larger than the thickness of the veins attached to the node.

The core defect boundary 145 comprises the inwardly-facing veins of the innermost ring of cells that surround the core defect 110.

In practice, for triangular lattice structures that have a large air-filling fraction, for example above 75%, most of the cladding holes 105 assume a generally hexagonal form, as shown in Figure 1, and the veins are generally straight.

The cells forming the innermost ring around the boundary of the core defect, which are referred to herein as "**boundary cells**", have one of two general shapes. A first kind of boundary cell 125 is generally hexagonal and has an innermost vein 130 that forms a relatively shorter side of the core defect boundary 145. A second kind of boundary cell 135 has a generally pentagonal form and has an innermost vein 140 that forms a relatively longer side of the core defect boundary 145.

Referring again to Figure 1, there are twelve boundary cells 125, 135 and twelve nodes 150, which are referred to herein as "**boundary nodes**", around the core defect boundary 145. Specifically, as defined herein, there is a boundary node 150 wherever a vein between two neighbouring boundary cells meets the core defect boundary 145. In Figure 1, these boundary nodes 150 have slightly smaller diameters than the cladding nodes 160. Additionally, there is an enlarged region

165, "bead" or "**nodule**", of silica at the mid point of each relatively longer side of the core defect boundary 145. These nodules 165 coincide with the mid-point along the inner-facing vein 140 of each pentagonal boundary cell 135. The nodules 165 may result from a possible manufacturing process used to form the structure in Figure 1, as will be described in more detail below. For the present purposes, the veins 130 & 140 that make up the core defect boundary are known as "**boundary veins**".

In the prior art, photonic band-gap fibres typically comprise either plural concentric layers of dielectric material surrounding a core, to form an omni-directional waveguide, or a microstructured photonic band-gap cladding, comprising a triangular lattice of hexagonal holes, surrounding a core region. In the latter kind of band-gap fibre, there is a core defect boundary but the shape and form of the boundary has typically been a simple function or artefact of the pre-form and manufacturing process used to make the fibre.

As will be described below, it is possible to control the diameters of particular nodes and the existence or size of nodules along the core defect boundary during manufacture of a fibre.

The structure in Figure 1 and each of the following examples of different structures closely resemble practical optical fibre structures, which have either been made or may be made according to known processes or the processes described hereinafter. The structures share the following common characteristics:

a pitch Λ of the cladding chosen between values of approximately 3μm and 6μm (this value may be chosen to position core-guided modes at an appropriate wavelength for a particular application);

a thickness t of the cladding veins of 0.0548 times the chosen pitch Λ of the cladding structure (or simply 0.0548Λ);

an air-filling fraction (AFF) in the cladding of approximately 87.5%.

The present inventors have determined that it is possible to control the performance of PBG fibres in particular by aiming to maximise the amount of light that propagates in air within the fibre structure, even if some light is not in the core, in order to benefit from the properties of PBG fibres, such as reduced absorption, non-linearity and, in addition, reduced mode coupling.

In particular, the inventors have identified the importance of the shape of the boundary for controlling the amount of light that propagates in air within the structure and for controlling the F-factor of the structure.

The core-cladding interface region of an air core PBG waveguide such as a photonic crystal fibre can be designed to exploit an anti-resonance effect to enhance the fraction of the mode power which resides in air. The geometry giving rise to the anti-resonance discussed here is based on a number of substantially localised regions of silica (nodules 165) placed on the core surround.

As described above, Figure 1 shows examples of locally concentrated high index regions (nodules 165) encircling an air core 110. Thin silica veins or struts 130, 140 connect the nodules together. Those struts directly connect onto to the PBG cladding region. If the struts connecting the concentrated regions of silica are thin, having a thickness less than 0.15 times the operational wavelength λ (which they are in the case of Figure 1), then the struts 130,140 connecting the localised high index regions do not themselves induce an anti-resonance effect; the anti-resonance is associated with substantially isolated high index regions 165. Indeed, it is found that localised regions of high index on a

thin core surround can confine light better than a continuous core surround which possesses an approximately even density of silica, although alternatively a continuous core surround can be optimised, as described in co-pending International Patent Application.

The fibre of Figure 1 has a structure similar to structures disclosed in several prior art publications, for example, "Low Loss (13 dB/km) Air Core Photonic Bandgap Fibre", Venkataraman *et al.*, Proc. ECOC 2002, Copenhagen; "Interferometric Chromatic Dispersion Measurement of Photonic Band-gap Fiber", Mueller *et al.*, Proc. SPIE 2002, Vol. 4870, Boston; "Photonic Crystal Fibres", West *et al.*, Proc. ECOC 2001, paper ThA22, Vol. 4, Amsterdam; and "Photonic Crystal Fibers: Effective-Index and Band-Gap Guidance", Gallagher *et al.*, Photonic Crystals and Light Localization in the 21st Century, pp. 305-320, Kluver (ISBN 0-7923-6947-5); "Dispersion and nonlinear propagation in air-core photonic band-gap fibers", Ouzounov, Ahmad, Gaeta, Müller, Venkataraman, Gallagher, Koch, CLEO 2003. The nodules present in those structures appear to be artefacts of the process used to manufacture the waveguides described. None of the prior art documents attach any significance to the features and there is no suggestion that the features exhibit any antiresonance effect. Moreover, the present inventors have investigated the structures disclosed in those prior art documents and have found nothing to suggest that those structures exhibit antiresonance: generally the nodules appear to be too small. However, the inventors have discovered that structures similar to the prior art structures do exhibit beneficial antiresonance effects. The inventors have discovered that presence or absence of these effects is very sensitive to the geometry of the structure, such as the dimensions of the nodules. Investigations by the inventors suggest that the described prior art structure has nodules with L in the range

0.27Λ to 0.45Λ and W in the range 0.11Λ to 0.21Λ; however, calculation of those values is based on an analysis of the SEM images in the prior art documents and the accuracy of the analysis is dependent upon the quality of those images. Those prior art structures, be they corresponding to those ranges or otherwise, are hereby disclaimed.

The mechanism by which anti-resonance due to localised regions of high index can occur may be understood by considering a corral of high index cylinders distributed around a closed loop, which may or may not be a circle. Examples of such a geometry are shown in Figure 2. The cylinders are everywhere surrounded by air. This system may be analysed quickly and accurately by employing a multiple scattering approach which fully exploits Mie-scattering theory; the field scattered from each cylinder is expanded in a multipole series. By applying the electromagnetic boundary conditions at the surfaces of the cylinders, an eigenvalue equation is derived. The method invokes radiating boundary conditions and can readily calculate leaky modes as well as guiding modes of the system; the former are obtained as solutions with complex β-values, with β the wavevector component along the direction of a cylinder axis. The guided modes, which are concentrated in the cylinders, satisfy $\mathrm{Re}[\beta] > \omega/c$, $\mathrm{Im}[\beta] = 0$. Only leaky modes with small imaginary β components, and which therefore leak only slowly, are retained; leakage rate is proportional to $\mathrm{Im}[\beta]$. $\mathrm{Re}[\beta]$ for the leaky mode solutions lies close to and just below the air light-line value ω/c.

A corral system, such as any of the examples shown in Figure 2, is found to support an LP_{01}-like leaky mode solution, which possesses an approximately Gaussian intensity profile centred at a point **p** in the air region which is enclosed by

the corral arrangement. Those solutions exist close to the air light line, $\beta = \omega/c$, so that the cylinders have a strong influence on the field. The cylinders force near nulls in the field intensity to occur close to their boundaries. For a given cylinder arrangement, by adjusting the size of the cylinders, the near nulls can be placed very close to the positions on the cylinder boundaries which lie closest to the point p. It is observed that $\mathrm{Im}[\beta]$ of the leaky mode solution is minimised when this occurs, meaning that the leakage rate is minimised. That is interpreted as an anti-resonance of the corral system; anti-resonances of more simple confining systems such as a dielectric ring are also signalled by a near-null occurring very close to the innermost dielectric interface. Figure 3(c) plots $\mathrm{Im}[\beta]$ against the cylinder diameter d for 6 cylinders evenly spaced around a circle (Figure 3(a)), with circle radii R=3.0, 4.5 and 6.0μm. (As is well known, the imaginary part of a refractive index corresponds physically to loss in the medium.) Also shown is $\mathrm{Im}[\beta]$ for a circular silica ring against its thickness d, for a ring radius of R=4.5μm (Figure 3(b)). The wavelength was set to λ=1.55μm. The superior confinement ability of the cylinder corral system at Λ=4.5μm is clearly observed.

The confining ability of a corral system is very dependent on the number and the location of the high index regions. If the regions are too far apart, such that for the LP_{01}-like leaky mode solution $\left|\sqrt{(\omega/c)^2 - \beta^2}\right| d$ exceeds approximately π, with d the largest separation of neighbouring high index regions in the corral, confinement will be weak. That is because the mode can resolve one or more of the gaps between the high index regions and so escape. That resolution argument can also be invoked to explain why the corral system supports far fewer leaky modes than a continuous element such

as a dielectric ring. The in-plane wavevector associated with higher order modes exceeds that of the more slowly varying LP_{01}-like mode, so that in the corral system, the higher order modes are more able to resolve the gaps between the high-index regions and leak away. This is an advantage of the corral system over the continuous design; the latter will generally support more modes within and nearby the band gap region and will therefore be more subject to mode coupling loss.

Optimum confinement induced by a number of identical, parallel high-index cylinders in a corral geometry is achieved when the cylinders are evenly spaced over the circumference of a circle. The optimum number of cylinders to place around the circle depends on its radius *R*. The width of the anti-resonance as a function of parameters such as cylinder radius or wavelength is increased by including more cylinders, but increasing the number of cylinders beyond a certain number will weaken the confinement that can be achieved.

Although the circular corral arrangement of cylinders is optimum, the LP_{01}-like leaky mode is able to accommodate significant movement in cylinder positions without incurring much increase in loss; the field associated with this mode redistributes itself to move the near nulls of the field so that they remain close to the cylinder boundaries. The loss penalty incurred by the movement is small as long as the area of the region existing within the corral exceeds $\sim 10\lambda^2$ and the separation of neighbouring cylinders remains below the resolution capacity of the mode. Figure 4 (a) and (b) shows the field intensity distribution for two different arrangements of 12 identical silica cylinders. In each case, the radius of the cylinders was chosen to correspond to anti-resonance. The maintenance of the positions of nulls close to the cylinder boundaries is clearly observed. Figure 5 compares the confinement ability of the two arrangements of 12 cylinders as a function of the cylinder diameter *d*. The

difference in the confinement ability of the two geometries is not severe. The confinement of the 12 cylinders evenly distributed around the hexagon, shown in Figure 4(b), is found to be virtually identical with 12 cylinders distributed evenly around a circle with an area equal to that of the hexagon.

As described above, the present inventors have determined that it is possible to control the performance of PBG fibres in particular by minimising the F-factor or maximising the amount of light that propagates in air within the fibre structure, even if some light is not in the core, in order to benefit from the properties of PBG fibres, such as reduced absorption, non-linearity and, in addition, reduced mode coupling. The present inventors use light power in air and F-factor as proxies to anti-resonance exhibited by the core boundary.

Corral systems comprising parallel elongated elements with different shapes in cross-section, such as ellipses, will behave similarly to the cylinder case described above. The confining ability of the anti-resonance will depend upon the shape and orientation of the elements; shapes with smooth surfaces with no locally high rates of curvature can be expected to induce better confinement than shapes which possess sharp features on their surfaces. Numerical simulations of air core PBG fibres which incorporate concentrated high index regions located around the core surround have shown that the corral anti-resonance effect remains present even in such a complex geometry. As a function of a parameter such as the size of the concentrated high index regions, broad maxima are observed in the power in air fraction η and broad minima appear in the factor F given by, Eqn. 5

$$F = \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{\oint_{\text{hole perimeters}} \mathrm{d}s \left|\mathbf{E}_0\right|^2}{\int_{\text{x-section}} \mathrm{d}S \left(\mathbf{E}_0 \wedge \mathbf{H}_0^*\right) \cdot \hat{\mathbf{z}}} \quad (5)$$

The quantity F measures field intensity at the dielectric interfaces and gives a direct relative measure of the strength of small-scale interface roughness scattering and provides an indication of the relative strength of mode coupling effects due to longer scale fluctuations. Upon examination of the LP_{01}-like mode field intensity profile at maximum η and minimum F, it is observed that near nulls occur close to the boundaries of the concentrated high index regions at locations closest to the position of peak intensity **p**. That confirms the mechanism in operation has the character of anti-resonance. The band gap cladding region can be interpreted as simply completing the confinement of the mode, which has already been substantially localised by the corral effect. Indeed, exploiting a corral anti-resonance can render the field intensity everywhere within the cladding to be more than 20dB below the peak intensity value. The analysis of the simple cylinder corral system presented above can be used to estimate the optimum number of concentrated elements to place around the core surround, give an indication of the size that these elements should have, and indicate the sensitivity to the parameters. Detailed numerical investigation of PBG photonic crystal fibres with concentrated index elements around the core supports this view.

In considering the variation of light in air and F-factor with any particular parameter, it should be noted that interactions between the mode being investigated and so-called surface modes near to the core boundary may lead to ghost resonance peaks. This kind of interaction is also identified in Müller, D. et al. "Measurement of photonic band-gap fiber transmission from 1.0 to 3.0 µm and impact of surface mode coupling." QTuL2 Proc. CLEO 2003 (2003). This paper supports

the present inventors' view that mode power from the air-guided modes may couple to lossy surface modes, which concentrate in or near to the core boundary. The result is increased loss, attendant increased F-factor and reduced light in air fraction. Indeed, for the case of a core boundary of uniform thickness, it is found that such mode crossings are suppressed for core thicknesses close to the anti-resonant value, but become abundant for core thicknesses away from anti-resonance. This surface mode exclusion property associated with the anti-resonance renders the curves for F-factor and amount of light in air smoother as they reach optimum values at core boundary thicknesses close to the anti-resonant point.

That an antiresonant core boundary is desirable for reducing the impact and/or number of surface modes in a PBG fibre is surprising and counter-intuitive, particularly when one considers the prior art, for example the teachings in the book "Photonic Crystals: Molding the Flow of Light". From such a reference, the skilled man would understand that surface modes can form due to the inclusion of a defect in a PBF structure; for example a hollow core defect in a PBG fibre. After appreciating this, it would appear sensible to include only a single defect in the structure; where plural defects could lead to plural sets of surface modes. Hence, it would appear reasonable to form a core defect boundary that, as closely as possible, matches the veins in the cladding structure. Otherwise, the core defect boundary might been 'seen' by the light as a additional defect, or even a waveguide in its own right, since it neither matches the core defect nor the cladding. In other words, having a core defect boundary that is significantly different, for example thicker in transverse cross section, than the individual cladding veins of the PBG cladding structure, would not have been a

natural choice for the skilled person who wanted to avoid the formation of surface modes.

In order to remove the ghost resonance peaks, it is either necessary to remove the surface states or adjust the operating point of the waveguide to avoid mode crossings. Moving the operating point for a given geometry can be achieved by varying the operating wavelength within the band gap and/or adjusting the pitch Λ of the photonic band-gap structure. Clearly the avoidance of mode crossings facilitated by a core surround close to anti-resonance will typically enable a wider wavelength bandwidth to be of practical use.

The inventors have investigated the effect of varying the size of nodules 165. To that end, an ellipse may be fitted to the nodule. Figure 6 shows how ellipses are fitted to nodules 165 in a waveguide boundary region.

The light power-in-air fraction of a particular structure is directly measurable. The method of measuring light power-in-air involves taking a near-field image of light as it leaves the structure, overlaying it on an SEM image of the structure and directly calculating the light power-in-air fraction from the overlap of the two images.

The F-factor can also be calculated for a real fibre structure by the following method. A Scanning Electron Micrograph (SEM) is taken of the cross-sectional structure of the fibre in question. An accurate representation of the structure, suitable for use in computer modelling, is obtained from the SEM by estimating the position of the structural boundaries throughout the cross-section. The mode profile is then calculated from the estimated structure using a computer modelling scheme described below. This provides knowledge of the electric and magnetic field distributions which enables both the numerator and denominator in Equation (5) above to be calculated.

The very small size of the thin veins in the structure means that great care must be taken when interpreting an SEM image. The apparent thickness of a vein in the image may be slightly different from the true thickness, but the small discrepancy will have a large impact on the light power-in-air fraction and F-factors determined from it. It is therefore advisable to confirm the validity of the process by which the model structure is determined from the SEM image, to yield a reliable fit. One way to confirm the fit would be through spectral measurements of the loss of the fibre, which often show peaks at particular wavelengths due to mode crossings. [see Smith *et al.*, "Low-loss hollow-core silica/air photonic bandgap fibre", Nature, Vol. 424 pp 657-659, 7 August 2003]

The % light in air may also be calculated by superimposing the modelled mode on the modelled structure. Figure 7 shows an idealised schematic of a portion of the fibre structure. Once the nodule is represented by an ellipse, the nodule is characterised by two parameters, the length L of the ellipse's major axis and the length W of its minor axis. In the example of Figure 1, the strut width is 0.05477Λ, the length L of the fitted ellipse is 0.5Λ and the length W is 0.5Λ/3.

Figures 8 and 9 show how the proportion of light in air and the F-factor, respectively, of mode guided in a fibre having a structure of the general form of Figure 1 varies with the parameters L and W, at an operating wavelength of 1550nm. In generating the plots of Figures 8 and 9, the fibre structure of Figure 1 was modelled on a computer and the proportion of light in air and the F-factor were calculated for various combinations of L and W. Each circle in the plots of Figures 8 and 9 represents one such combination of L and W; the diameter of the plotted circle is proportional to the proportion of light power in air or F-factor, with smaller circles representing better performance, that is a higher

proportion of light in air or a lower F-factor. The largest circle in Figures 8 and 9, at co-ordinate ($4\Lambda/12, 4\Lambda/36$) in each plot, corresponds to a % light in air of 96.7% and an a F-factor of 0.74 Λ^{-1}. The smallest circle in Figures 8 and 9, at co-ordinate ($5\Lambda/12, 6\Lambda/36$) in each plot, corresponds to a % light in air of 99.3% and an a F-factor of 0.13 Λ^{-1}.

Plots of the kind shown in Figures 8 and 9 have been shown to provide a reliable means for distinguishing between good and bad structures and ascertaining antiresonant core wall behaviour. Obviously, a more rigorous numerical analysis might involve plotting the proportion of light in air and F-factor for all values of wavelength within the band-gap for any one given structure, since the plots can vary slightly at different wavelengths, particularly in the vicinity of mode crossings, as already described.

For the purposes of comparing aspects of the performance of various different structures it is useful to consider the modes that are supported in the band gap of various PBG fibre structures. This may be achieved by solving Maxwell's vector-wave equation for the fibre structures, using known techniques. In brief, Maxwell's equations are recast in wave equation form and solved in a plane wave basis set using a variational scheme. An outline of the method may be found in Chapter 2 of the book "Photonic Crystals - Molding the Flow of Light", J.D. Joannopoulos et al., ©1995 Princeton University Press.

It can be seen that the performance is different in different regions of the plane, that is, for different values of L and W. Figure 10 (a) and (b) show examples of lines defining various regions of the L-W plane that are believed to be of particular interest for the structure of Figure 1. Other lines in addition to those shown in Figure 10 may be of interest. The structure of Figure 1 has a pitch of 3.2μm and is designed for guiding light centred on the wavelength

1.55μm; however the results of Figures 8 to 10 are independent of pitch and wavelength (when both are scaled congruently) and apply to a broad range of structures having the general form of Figure 1.

In another example of an embodiment of the invention (Figure 11) a waveguide is provided having a larger core region 210. Core region 210 corresponds to 19 unit cells of the cladding structure of the waveguide, whereas core 110 in Figure 1 corresponds to 7 unit cells. Omission of the ring of 12 unit cells results in a different boundary from the boundary of the waveguide of Figure 1. The boundary of the Figure 11 waveguide has 12 longer veins 240 and 6 shorter veins (in Figure 1, there were 6 longer veins 140 and six shorter veins 130). Nodules 265 are provided on each of the longer veins 240. The nodules are elliptical in form with a major axis of length 0.5Λ and a minor axis of length 0.1667Λ. The cladding air filling fraction is 87.5%. Away from nodules 165, the core wall thickness is 0.055Λ.

The performance of the structure of Figure 11 is significantly improved over that of Figure 1. For the 7-cell structure, best results achieved were 99.3% light in the low refractive index regions (i.e. air) and an F-factor of 0.1345 Λ^{-1}. For the 19-cell structure, 99.7% of the light is in the low refractive index regions and the F-factor is 0.0636 Λ^{-1}.

Field intensity plots (Figure 12 (i) and (ii)) show that light in the two orthogonal polarisation modes ((a) and (b)) guided in the fibre is concentrated in a single-lobed pattern (resembling the fundamental mode of a standard optical fibre, although the pattern guided in the present fibre consists of multiple transverse modes). Figure 12 (iii) shows the distribution of F-factor, that is, which air-silica boundaries are contributing most to the F-factor. A bright pixel shows a section of boundary that is interacting with a high intensity part of the field. The plots demonstrate that there is

significant overlap of the light in the guided mode with the core boundary and illustrate the importance of nodule dimensions.

Other PBG waveguides having different PBG boundary shapes are shown in Figures 13 to 16. In Figure 13, nodules 365 are at the mid-points of the longer veins, as in previously described embodiments, but in this case are semi-elliptical in shape, being flat on the surface of the vein furthest from the core and elliptical on the surface of the vein closest to the core. Conversely, in Figure 14, nodules 465 are semi-elliptical in shape, being flat on the surface of the vein closest to the core and elliptical on the surface of the vein furthest from the core.

In the embodiment of Figure 15, the waveguide has a 'nineteen-cell' core, as in Figure 11, but in this case the nodules 565 are nodes joining pairs of longer veins at their ends and also joining them to other parts of the photonic band-gap structure.

In the embodiment of Figure 16, the waveguide again has a 'nineteen-cell core', but in this case the nodules 656 are provided form the six shortest veins in the boundary region.

It will thus be understood that the nodules may take any suitable form and location in the boundary. For example, the nodules need not be at the mid-point of a vein and may indeed be at a node joining two veins. Furthermore, the nodules need not be elliptical or circular in cross-section; they may for example be 'lumpy', for example a 'double lump' may be made by fusing two side-by-side rods together during drawing of the fibre.

With reference to Figure 17, fibres such as that of Figure 1 may be made from a preform 1100 comprising a stack of hexagonal capillaries 1105. The hexagonal capillaries 1105 each have a circular bore. The cladding nodes 160 and boundary nodes 150 (from Figure 1) of the PBG fibre structure

result from the significant volume of glass that is present in the perform 1100 wherever the corners 1110, 1115 of neighbouring capillaries meet. The nodules 165 are formed from the glass of the inwardly-facing corners 1120 of the capillaries that bound an inner region 1125 of the pre-form 1100, which is to become the core defect region 110 of a PBG fibre structure. These corners 1120, and the two sides of each capillary that meet at the corners, recede due to surface tension as the stack of capillaries is heated and drawn. Such recession turns the two sides and the corner 1120 into a boundary vein 140, with a nodule 165. The inner region 1125 may be formed by omitting the inner seven capillaries from the pre-form and, for example, supporting the outer capillaries using truncated capillaries at either end of the stack, as described in PCT/GB00/01249 (described above) or by etching away glass from inner capillaries in accordance with either PCT/GB00/01249 or US 6,444,133 mentioned above.

Figure 18 illustrates one way of arranging a stack of capillaries 1200 to be drawn into a pre-form and fibre of the kind shown in Figure 16. The cladding is formed by stacking round cross section capillaries 1205 in a close-packed, triangular lattice arrangement. The cladding capillaries 1205 have an outer diameter of 1.04mm and a wall thickness of 40μm. The inner region 1210 of the stack contains a large diameter capillary 1215 having an outer diameter of 4.46mm and a wall thickness of 40μm. The large diameter capillary 1215 supports the cladding capillaries while the stack is being formed and eventually becomes part of the material that forms a core defect boundary 145.

Interstitial voids 1220 that form between each close-packed, triangular group of three cladding capillaries are each packed with a glass rod 1225, which has an outer diameter of 0.498mm. The rods 1225 are inserted into the voids 1220 after the capillaries have been stacked. The rods 1225 that

are packed in voids 1220 assist in forming cladding nodes 160, which have a diameter that is significantly greater than the thickness of the veins that meet at the nodes. Omission of a rod from a void in the cladding would lead to the formation of a cladding node that has a significantly smaller diameter.

In a similar manner, rods 1230 are inserted into voids between the large-diameter capillary 1215 and between pairs of capillaries 1205 that are closest to the large diameter capillary 1215. (The triangular cladding structure naturally divides the innermost ring of capillaries 1205 into such pairs.) Rods 1230 are kept in place by thin-walled capillaries 1239. Smaller gaps 1235 formed within the pairs are not filled. Rods 1230 form, with silica from surrounding capillaries, nodules 665, while the silica around gaps 1235 forms veins.

The stack 1200 is arranged as described with reference to Figure 18 and is then over-clad with a further, relatively thick walled capillary (not shown), which is large enough to contain the stack and, at the same time, small enough to hold the capillaries and rods in place. The entire over-clad stack is then heated and drawn into a pre-form, during which time all the interstitial voids at the boundary, and remaining voids between the glass rods and the cladding capillaries, collapse due to surface tension. The pre-form is, again, over-clad with a final, thick silica cladding and is heated and drawn into optical fibre in a known way. If surface tension alone is insufficient to collapse the interstitial voids, a vacuum may be applied to the interstitial voids of the pre-form, for example according to the process described in WO 00/49436 (The University of Bath).

Figures 19a and 19b illustrate alternative preform stacks used for making fibres according to embodiments of the present invention. The stack in Figure 19a includes a large diameter core capillary replacing seven cladding capillaries. Six rods

are fused onto the large diameter capillary; each one coinciding with a point where a cladding capillary abuts the large diameter capillary. This stack is suitable for making a fibre of the kind shown in Figure 1 or in Figure 13. The stack in Figure 19b is similar to the stack in Figure 19a, apart from the large diameter capillary replacing nineteen cladding capillaries and there being twelve rods attached to the large diameter capillary; each one coinciding with a point where a cladding capillary abuts the large diameter capillary. This stack is suitable for making a fibre of the kind illustrated in Figure 11.

In a further alternative way to form the fibre, a graphite insert is provided as an alternative to large diameter capillary 1215. The graphite insert is shaped to be a mould for the desired boundary shape. During a first drawing step, the stack of capillaries 1205 collapses onto the graphite insert and is moulded to its shape. As the partly drawn fibre cools, the graphite insert becomes loose and is removed before a second drawing step, in which the final fibre is drawn.

A further alternative way to form the fibre is by using the process described in PCT/GB00/01249 (described above), wherein the inner capillaries are replaced by truncated capillaries, which support the outer capillaries at either end of the stack. The stack may be drawn to an optical fibre in the normal way, and the parts of the fibre incorporating the truncated capillary material may be discarded. In principle, truncated capillaries may also be used to support the stack part way along its length.

Figure 20a is a photograph, taken by the present inventors through a microscope, of a rod fused to a large diameter capillary before the capillary is introduced into a pre-form stack, for example of the kind illustrated in Figure 19a. Whether the rod becomes a bead along a core boundary

(for example as shown in Figure 1) or a relatively more pronounced nodule protruding only from one side of a core boundary (for example as shown in Figure 13) can be controlled by the fibre drawing conditions. For example, hotter drawing conditions under lower tension permit a rod and boundary to fuse completely, thereby forming a bead. In contrast, a colder draw under higher tension prevents complete fusing of the rod and core boundary, leaving the rod as a nodule on the surface of the core boundary in a final fibre structure. Clearly, a nodule can be arranged to form on an inner or outer periphery of a core boundary, depending on whether the respective rod is positioned on an inner or outer periphery of a large diameter capillary of the pre-form stack. The properties of a final fibre structure are expected to vary with bead and/or nodule size and placement.

Figure 20b is a SEM image of a bead, magnified by a factor of about 4000, which forms part of a PBG cladding structure according to an embodiment of the present invention. As shown, the bead has formed along a relatively shorter vein of the cladding structure. The structure is a result of heating and drawing a preform containing the rod shown in Figure 20a. The drawing conditions included a heating temperature of about 2050°C, a draw speed of about $2ms^{-1}$ and a draw tension of about 240g. Clearly, the rod has fused completely with the capillary under these drawing conditions. It is expected that cooler and/or faster drawing conditions would lead to the formation of a nodule on the inner surface only of the capillary.

Figure 21a is a photograph taken through a microscope of a rod fused to the outer periphery of a core boundary in a preform stack. In this case, the rod was initially fused inside a cladding capillary and the cladding capillary was rotated so that the rod was aligned with the point where the cladding capillary abutted the large diameter core capillary

in the stack. The SEM image in Figure 21b shows how the rod becomes a bead along the core boundary of a fibre drawn from a preform of the kind shown in Figure 21a.

Figure 22 is a diagram of a transmission system 2200 comprising an optical transmitter 2210, an optical receiver 2220 and an optical fibre 2230 between the transmitter and receiver. The optical fibre 2230 comprises along at least a part of its length an optical fibre according to an embodiment of the present invention. Other components or systems, for example to compensate for dispersion and loss, would typically be included in the system but are not shown in Figure 22 for the sake of convenience only.

The skilled person will appreciate that the various structures described above may be manufactured using the described manufacturing process or a prior art processes. For example, rather than using a stacking and drawing approach to manufacture, a pre-form may be made using a known extrusion process and then that pre-form may be drawn into an optical fibre in the normal way.

In addition, the skilled person will appreciate that while the examples provided above relate exclusively to PBG fibre cladding structures comprising triangular arrays, the present invention is in no way limited to such cladding structures. For example, the invention could relate equally to square lattice structures, or structures that are not close-packed. In general, the inventors propose that given a cladding structure that provides a PBG and a core defect in the cladding structure that supports guided modes, the form of the boundary at the interface between the core defect and the cladding structure will have a significant impact on the characteristics of the waveguide, as described herein.

It will be appreciated that, in practical fibres, it is difficult to control the fabrication process to achieve exact dimensions, for example, of core boundary nodules. However,

the antiresonance minima in F-number (maxima in light in air fraction) are quite broad, compared with resonances, which are characterised by sharp peaks at certain thicknesses of core boundary. Thus, a core boundary nodule having dimensions in the region of an antiresonance minimum, even if not exactly at the minimum, will still provide an advantage over other waveguides. It is expected that, as fabrication processes improve, it will be possible to make a core boundary having nodules having a shape very close to desired shape. There may be reasons for making a core boundary nodule which is not optimum according to a strict antiresonance analysis. One exemplary reason may be mode crossings, which can have deleterious effects of the transmission characteristics of a fibre, as discussed above.

The skilled person will appreciate that the structures described herein fit on a continuum comprising a huge number of different structures, for example having different combinations of core defect size, boundary node size, boundary vein thickness and, in general, boundary and cladding form. Clearly, it would be impractical to illustrate each and every variant of PBG waveguide structure herein. In particular, where numerical values or ranges of values are given herein for a particular parameter, all combinations with values or ranges of values of other parameters given herein are disclosed unless such combinations are not physically possible. As such, the skilled person will accept that the present invention is limited in scope only by the present claims.

CLAIMS

1. An elongate waveguide for guiding light comprising:

a core, comprising an elongate region of relatively low refractive index; and

a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core;

characterised in that the boundary region has a shape such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 95% of the guided light is in the regions of relatively low refractive index in the waveguide.

2. A waveguide as claimed in claim 1, in which the boundary region has a shape such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 1% of the guided light is in the regions of relatively low refractive index in the photonic bandgap structure.

3. A waveguide as claimed in any preceding claim, in which the boundary region has a shape such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 50% of the guided light is in the region of relatively low refractive index in the core.

4. A waveguide as claimed in any preceding claim, in which the boundary region has a shape such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than 0.23 μm^{-1} (0.7 Λ^{-1}).

5. An elongate waveguide for guiding light comprising:

a core, comprising an elongate region of relatively low refractive index; and

a photonic bandgap structure arranged to provide a photonic bandgap over a range of frequencies of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core;

characterised in that the boundary region has a shape such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than 0.23 μm^{-1} ($0.7\ \Lambda^{-1}$).

6. A waveguide as claimed in any preceding claim, in which in the transverse cross section, the photonic bandgap structure comprises an array of the relatively low refractive index regions separated from one another by the relatively high refractive index regions.

7. A waveguide as claimed in claim 6, in which the array is substantially periodic.

8. A waveguide as claimed in claim 6 or claim 7, in which the array is a substantially triangular array.

9. A waveguide as claimed in any of claims 6 to 8, in which the array has a characteristic primitive unit cell and a pitch Λ.

10. A waveguide as claimed in any preceding claim, in which the boundary region comprises, in the transverse cross-section, a plurality of relatively high refractive index boundary veins joined end-to-end around the boundary between boundary nodes, each boundary vein being joined between a leading boundary node and a following boundary node, and each boundary node being joined between two boundary veins and to a relatively high refractive index region of the photonic bandgap structure.

11. A waveguide as claimed in claim 10, in which at least one of the boundary veins comprises, along its length or at its end, a nodule.

12. A waveguide as claimed in claim 11, in which the nodule has a substantially elliptical shape in the transverse cross-section, such that an ellipse having a major axis of length L and a minor axis of length W substantially fits to the shape of the nodule in the transverse cross-section.

13. A waveguide as claimed in claim 12, in which the major axis extends along the boundary vein in which the nodule is comprised.

14. A waveguide as claimed in claim 12 or 13, in which the lengths of the minor and major axes are substantially equal, that is $W \approx L$.

15. A waveguide as claimed in claim 12 or 13, in which $W \leq 0.467L$.

16. A waveguide as claimed in claim 15, in which the length of the minor axis is substantially equal to one-third of the length of the major axis, that is $W \approx \frac{L}{3}$.

17. A waveguide as claimed in any of claims 12 to 16, in which $W \geq 0.238L$.

18. A waveguide as claimed in claim 12 or claim 13, arranged to guide light at a wavelength λ_1, which is in the ultraviolet, visible or infrared parts of the electromagnetic spectrum.

19. A waveguide as claimed in any of claims 12 to 18, arranged to guide light at a wavelength λ_2, wherein light guided at the wavelength λ_2 exhibits lower loss than light guided in the waveguide at any other wavelength.

20. A waveguide as claimed in claim 18 or 19, there being a parameter X that is equal to the wavelength λ_1 or the wavelength λ_2.

21. A waveguide as claimed in any of claims 12 to 19, when dependent on claim 9, there being a parameter X that is equal to the wavelength λ_1, the wavelength λ_2 or the pitch Λ.

22. A waveguide as claimed in claim 20 or 21, in which $L \geq \frac{5X}{12}$.

23. A waveguide as claimed in claim 22, in which the length of the major axis is substantially equal to half the pitch, that is $L \approx \frac{X}{2}$.

24. A waveguide as claimed in any of claims 20 to 23, in which $L \leq \frac{7X}{12}$.

25. A waveguide as claimed in any of claims 20 to 24, in which $W > \frac{X}{18}$.

26. A waveguide as claimed in claim 25, in which $W > \frac{5X}{36}$.

27. A waveguide as claimed in claim 26, in which the length of the minor axis is substantially equal to one-sixth of the pitch, that is $W \approx \frac{X}{6}$.

28. A waveguide as claimed in any of claims 20 to 27, in which $W \leq \frac{7X}{36}$.

29. A waveguide as claimed in any of claims 20 to 28, in which $L \times W \geq 0.058X^2$.

30. A waveguide as claimed in claim 29, in which the product of the lengths of the major and minor axes is substantially equal to one-twelfth the square of the pitch, that is $L \times W \approx \frac{X^2}{12}$.

31. A waveguide as claimed in any of claims 20 to claim 30, in which $L \times W \leq 0.113X^2$.

32. A waveguide as claimed in any of claims 20 to claim 31, in which $W \leq \left(\frac{1}{18} + \frac{L}{3}\right)X$.

33. A waveguide as claimed in any of claims 20 to claim 32, in which $W \geq \left(-\frac{1}{18} + \frac{L}{3}\right)X$.

34. A waveguide as claimed in any of claims 20 to claim 33, in which $W \geq \left(\frac{5}{18} - \frac{L}{3}\right)X$.

35. A waveguide as claimed in any of claims 20 to claim 34, in which $W \leq \left(\frac{7}{18} - \frac{L}{3}\right)X$.

36. A waveguide as claimed in any of claims 20 to claim 35, in which $W \geq (-0.133 + 0.467L)X$.

37. A waveguide as claimed in any of claims 20 to claim 36, in which $W \leq (0.095 + 0.238L)X$.

38. A waveguide as claimed in any of claims 20 to claim 37, in which $W \geq (0.333 - 0.467L)X$.

39. A waveguide as claimed in any of claims 20 to claim 38, in which $W \leq (0.333 - 0.238L)X$.

40. A waveguide as claimed in any of claims 20 to claim 39, in which $W \leq (0.467 - 0.467L)X$.

41. A waveguide as claimed in any of claims 20 to claim 40, in which $W \leq (0.238 - 0.238L)X$.

42. A waveguide as claimed in any preceding claim, in which the core has, in the transverse cross-section, an area that is significantly greater than the area of at least some of the relatively low refractive index regions of the photonic bandgap structure.

43. A waveguide as claimed in claim 42, in which the core has, in the transverse cross-section, an area that is greater than twice the area of at least some of the relatively low refractive index regions of the photonic bandgap structure.

44. A waveguide as claimed in any preceding claim, in which the core has, in the transverse cross-section, an area that is greater than the area of each of the relatively low refractive index regions of the photonic bandgap structure.

45. A waveguide as claimed in any preceding claim, in which at least some of the relatively low refractive index regions are voids filled with air or under vacuum.

46. A waveguide as claimed in any preceding claim, in which at least some of the relatively low refractive index regions are voids filled with a gas other than air or a liquid.

47. A waveguide as claimed in any preceding claim, in which at least some of the relatively high refractive index regions comprise silica glass.

48. A waveguide as claimed in any preceding claim, in which the relatively low refractive index regions make up more than 75% by volume of the photonic bandgap structure.

49. A waveguide as claimed in claim 48, in which the relatively low refractive index regions make around 87.5% by volume of the photonic bandgap structure.

50. A waveguide as claimed in any preceding claim, in which at least two of the higher index regions in the photonic bandgap structure are connected to each other.

51. A waveguide as claimed in claim 50, in which the higher index regions in the photonic bandgap structure are interconnected.

52. An optical fibre comprising a waveguide as claimed in any preceding claim.

53. A transmission line for carrying data between a transmitter and a receiver, the transmission line including along at least part of its length a fibre as claimed in claim 52.

54. Data conditioned by having been transmitted through a waveguide as claimed in any of claims 1 to 51.

55. A method of forming an elongate waveguide, comprising the steps:

forming a preform stack by stacking a plurality of elongate elements;

omitting, or substantially removing at least one elongate element from an inner region of the stack; and

heating and drawing the stack, in one or more steps, into a waveguide according to any of claims 1 to 51.

56. A method of forming elongate waveguide for guiding light, comprising the steps:

(a) simulating the waveguide in a computer model, the waveguide comprising a core, comprising an elongate region of relatively low refractive index and a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core, wherein properties of the boundary region are represented in the computer model by parameters;

(b) finding a set of values of the parameters that, according to the model, increases or maximises how much of the light guided by the waveguide is in the regions of relatively low refractive index in the waveguide.

57. A method of forming elongate waveguide for guiding light, comprising the steps:

(a) simulating the waveguide in a computer model, the waveguide comprising a core, comprising an elongate region of relatively low refractive index, and a photonic bandgap structure arranged to provide a photonic bandgap over a range of frequencies of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index,

including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core, wherein properties of the boundary region are represented in the computer model by parameters;

(b) finding a set of values of the parameters that, according to the model, decreases or minimises the F-factor of the waveguide.

58. A method as claimed in claim 56 or 57, in which the boundary region comprises, in the transverse cross-section, a plurality of relatively high refractive index boundary veins joined end-to-end around the boundary between boundary nodes, each boundary vein being joined between a leading boundary node and a following boundary node, and each boundary node being joined between two boundary veins and to a relatively high refractive index region of the photonic bandgap structure and at least one of the boundary veins comprises, along its length, a nodule, the nodule having a substantially elliptical shape in the transverse cross-section, such that an ellipse having a major axis of length L and a minor axis of length W substantially fits to the shape of the nodule in the transverse cross-section, wherein the parameters for which values are found comprise L and W.

59. An elongate waveguide for guiding light comprising:

a core, comprising an elongate region of relatively low refractive index; and

an outer structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region comprising a continuous shell of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core;

characterised in that the boundary region comprises a feature that is antiresonant at a wavelength of light guided in the waveguide.

60. A photonic crystal fibre comprising:

an outer structure comprising a periodic array of unit cells, each unit cell comprising a central region of a vacuum or a fluid and an outer region of a solid material, the periodic array having a pitch Λ; and

a core, comprising an elongate region of a vacuum or a fluid;

the outer structure including a boundary region comprising a plurality of veins of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core;

characterised in that the veins include nodules that are antiresonant at a wavelength of light guided in the waveguide.

61. An optical waveguide substantially as hereinbefore described, with reference to the accompanying drawings.

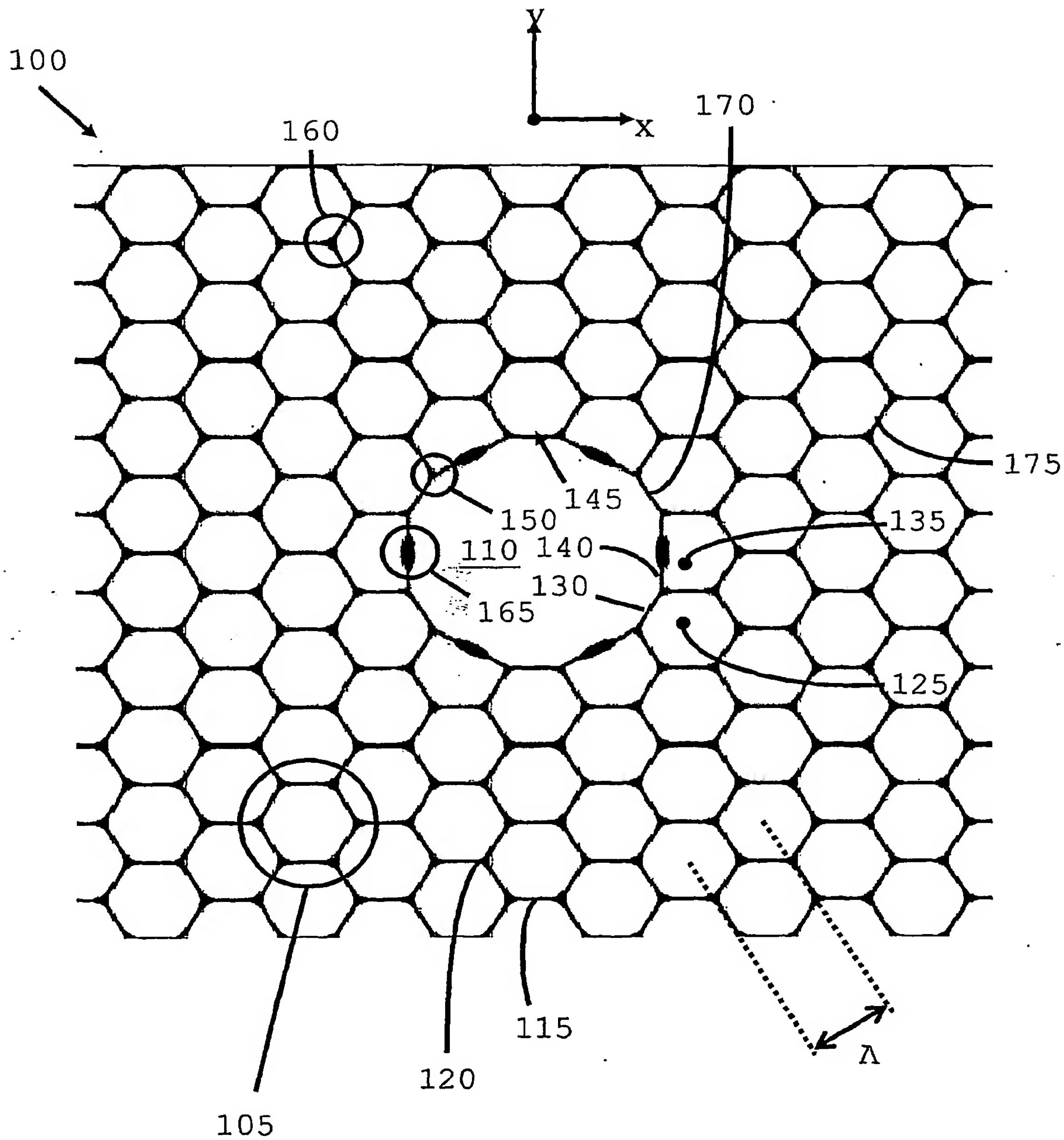


Figure 1

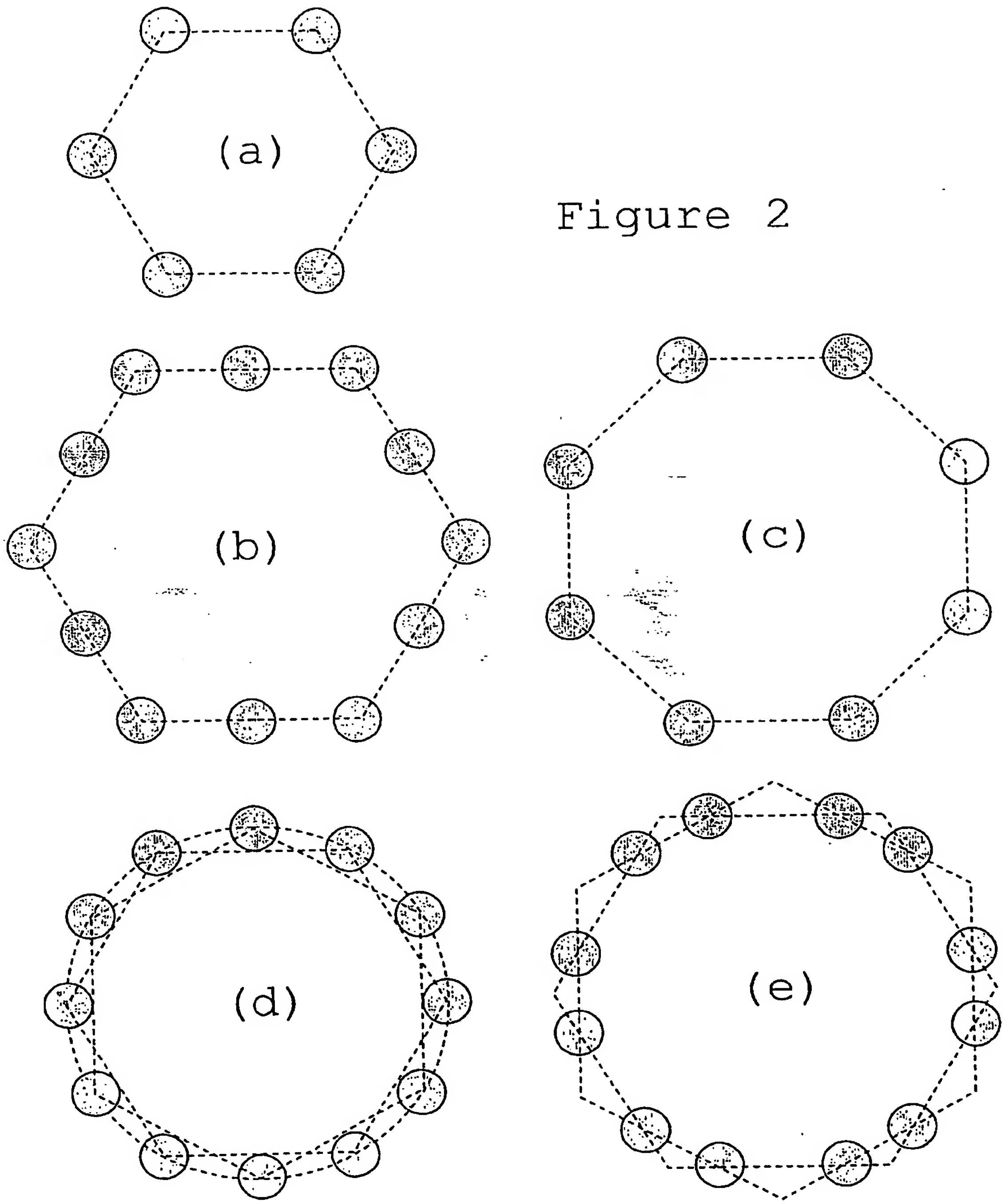


Figure 2

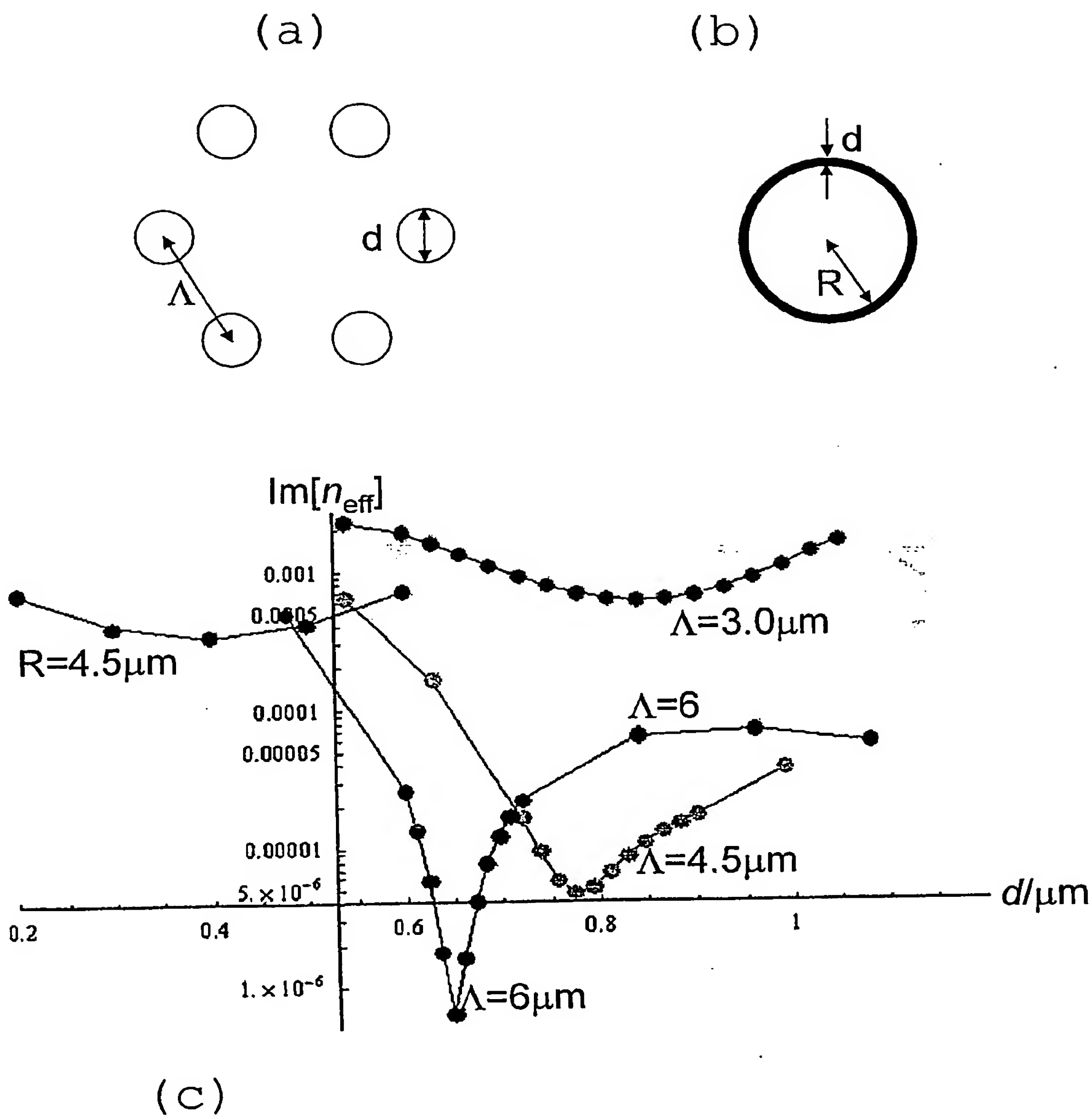
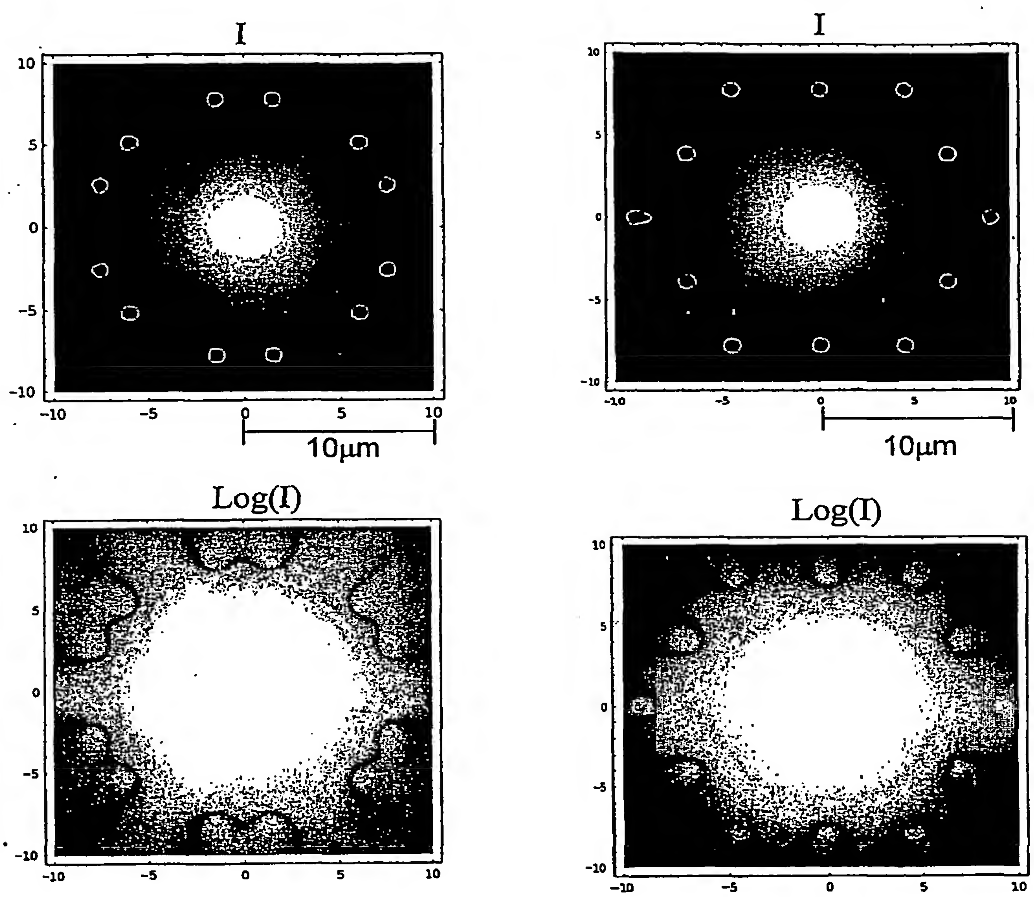

(a)
(b)
d
Λ
d
R
(c)
Im[n_{eff}]
0.001
0.0005
0.0001
0.00005
0.00001
5. × 10^-6
1. × 10^-6
0.2
0.4
0.6
0.8
1
d/μm
Λ=3.0μm
R=4.5μm
Λ=6
Λ=4.5μm
Λ=6μm

Figure 3


I
10
5
0
-5
-10
-10
-5
0
5
10
10μm
I
10
5
0
-5
-10
-10
-5
0
5
10
10μm
Log(I)
10
5
0
-5
-10
-10
-5
0
5
10
Log(I)
10
5
0
-5
-10
-10
-5
0
5
10

(a) (b)

Figure 4

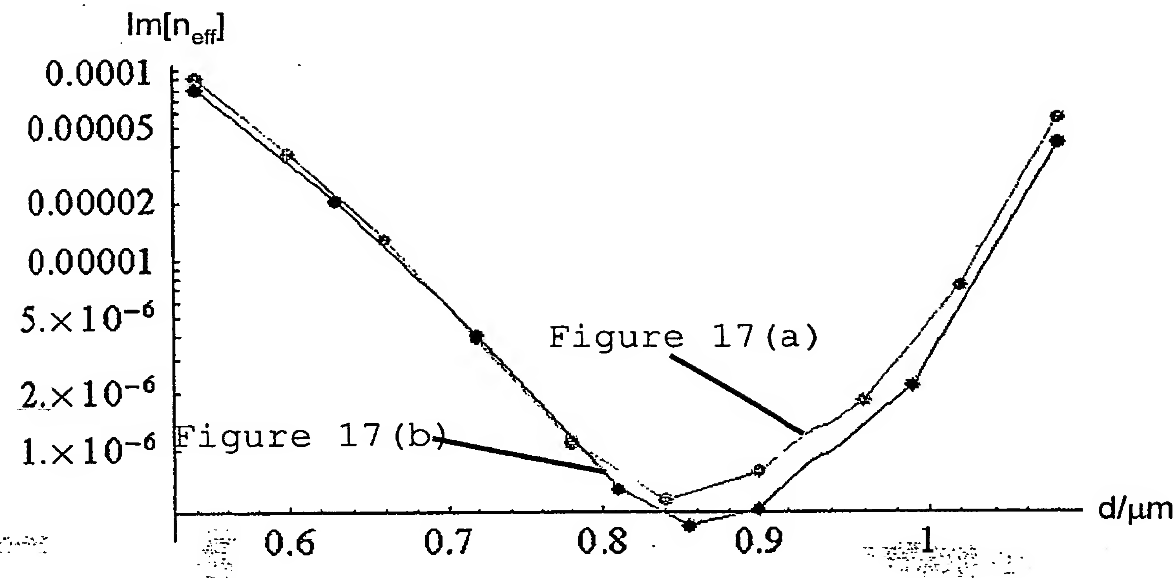

Im[n_eff]
0.0001
0.00005
0.00002
0.00001
5.×10⁻⁶
2.×10⁻⁶
1.×10⁻⁶
Figure 17(a)
Figure 17(b)
0.6
0.7
0.8
0.9
1
d/μm

Figure 5

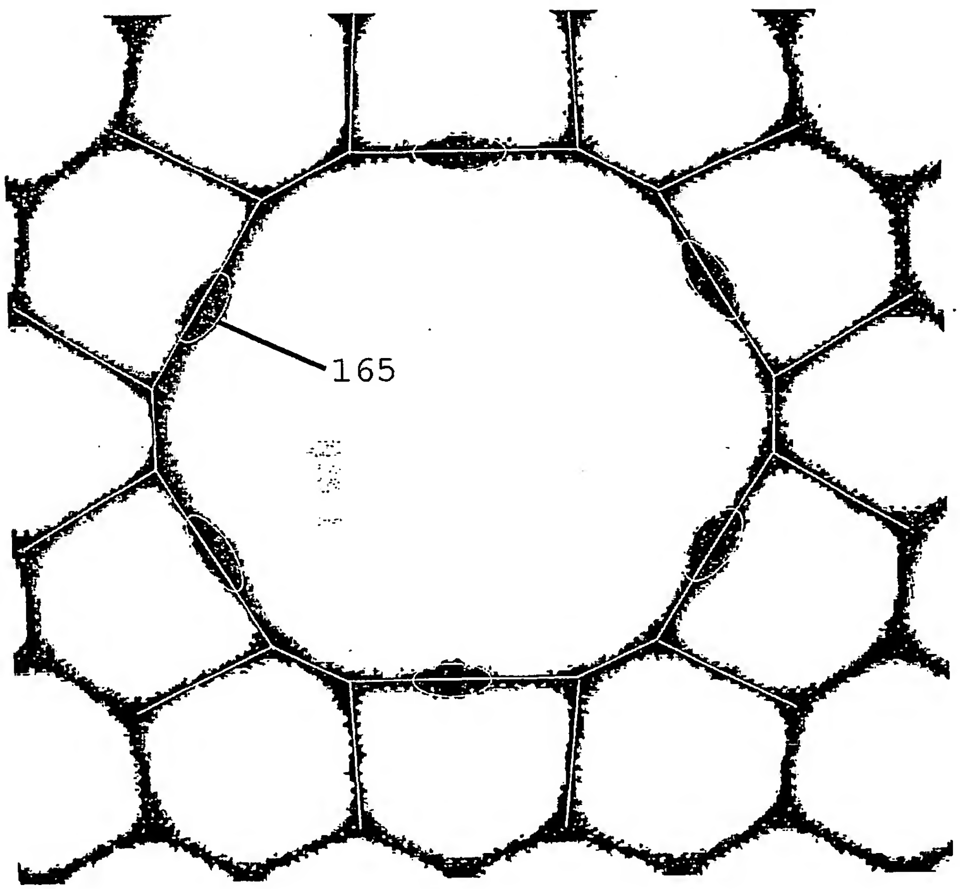


Figure 6

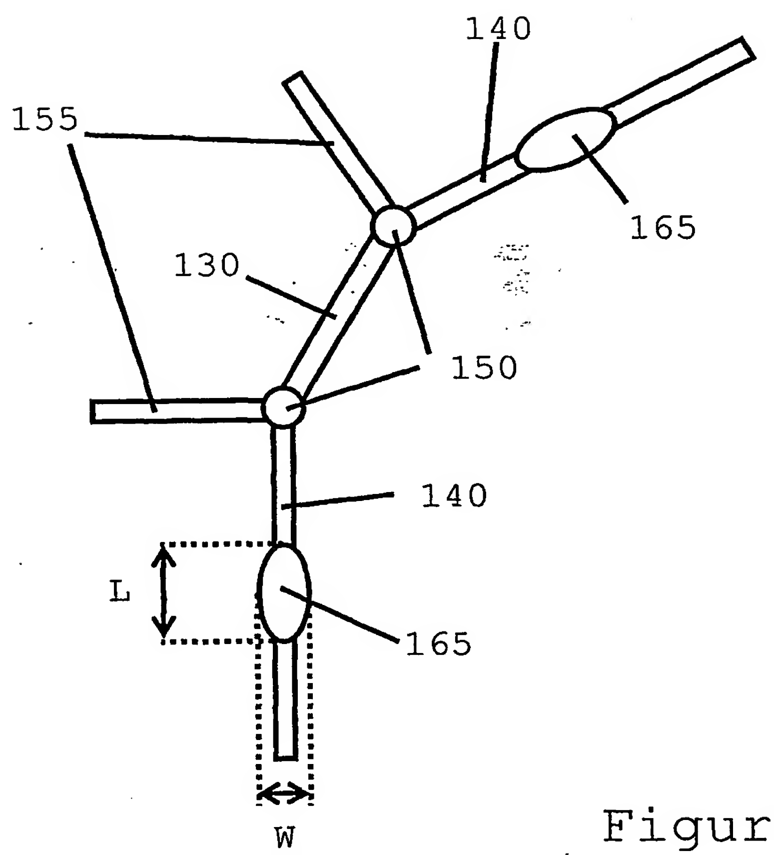


Figure 7

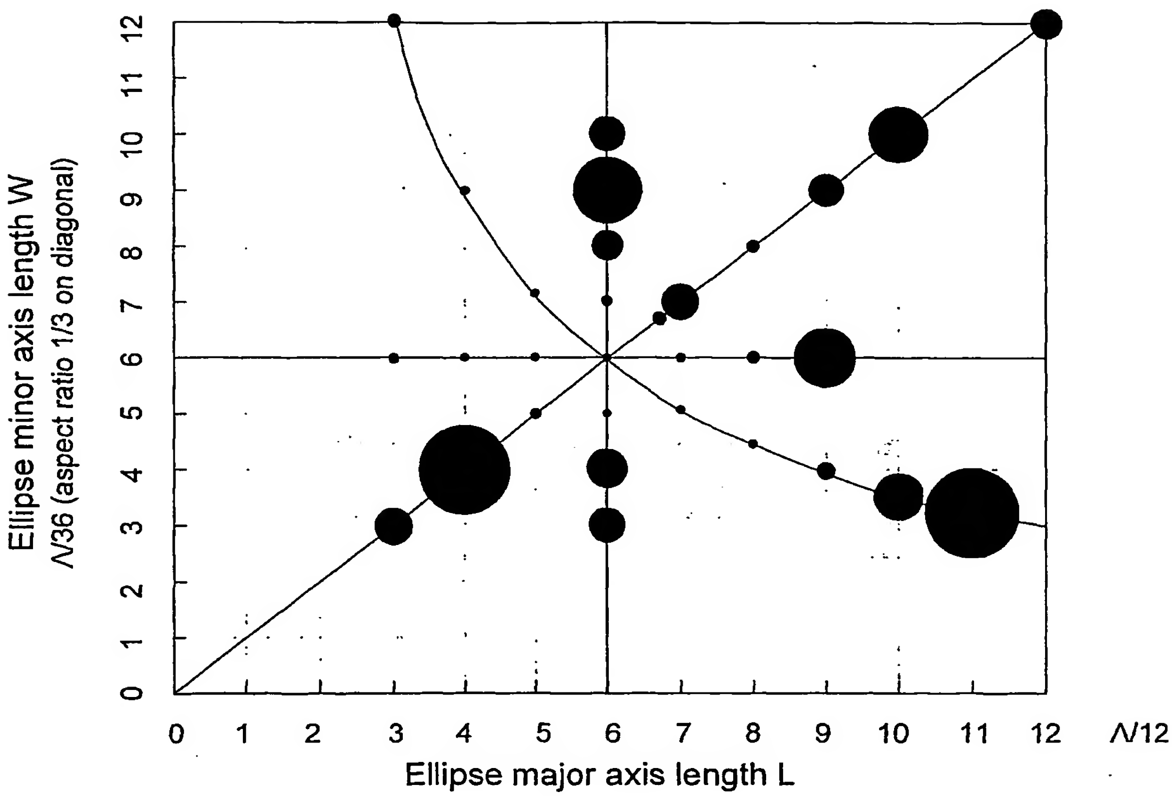

Ellipse minor axis length W
Λ/36 (aspect ratio 1/3 on diagonal)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
3
4
5
6
7
8
9
10
11
12
Λ/12
Ellipse major axis length L

Figure 8

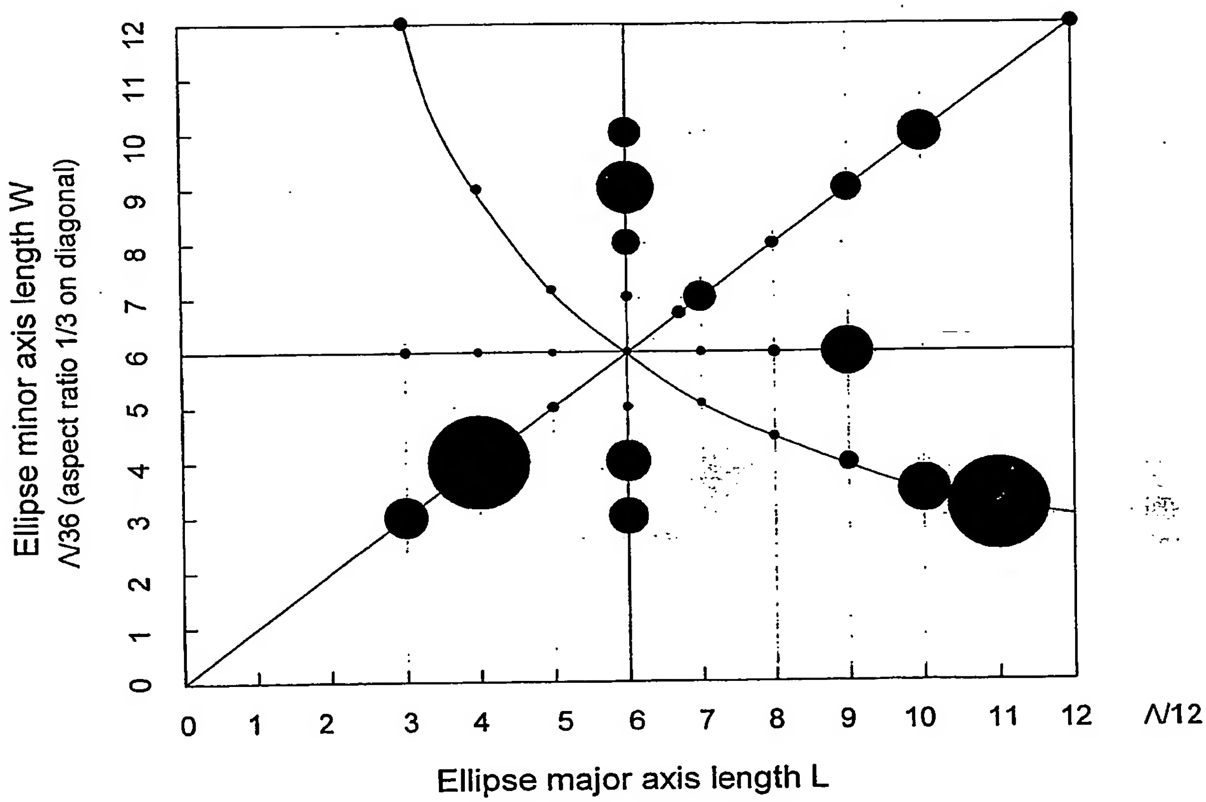

Ellipse minor axis length W
Λ/36 (aspect ratio 1/3 on diagonal)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
3
4
5
6
7
8
9
10
11
12
Λ/12
Ellipse major axis length L

Figure 9

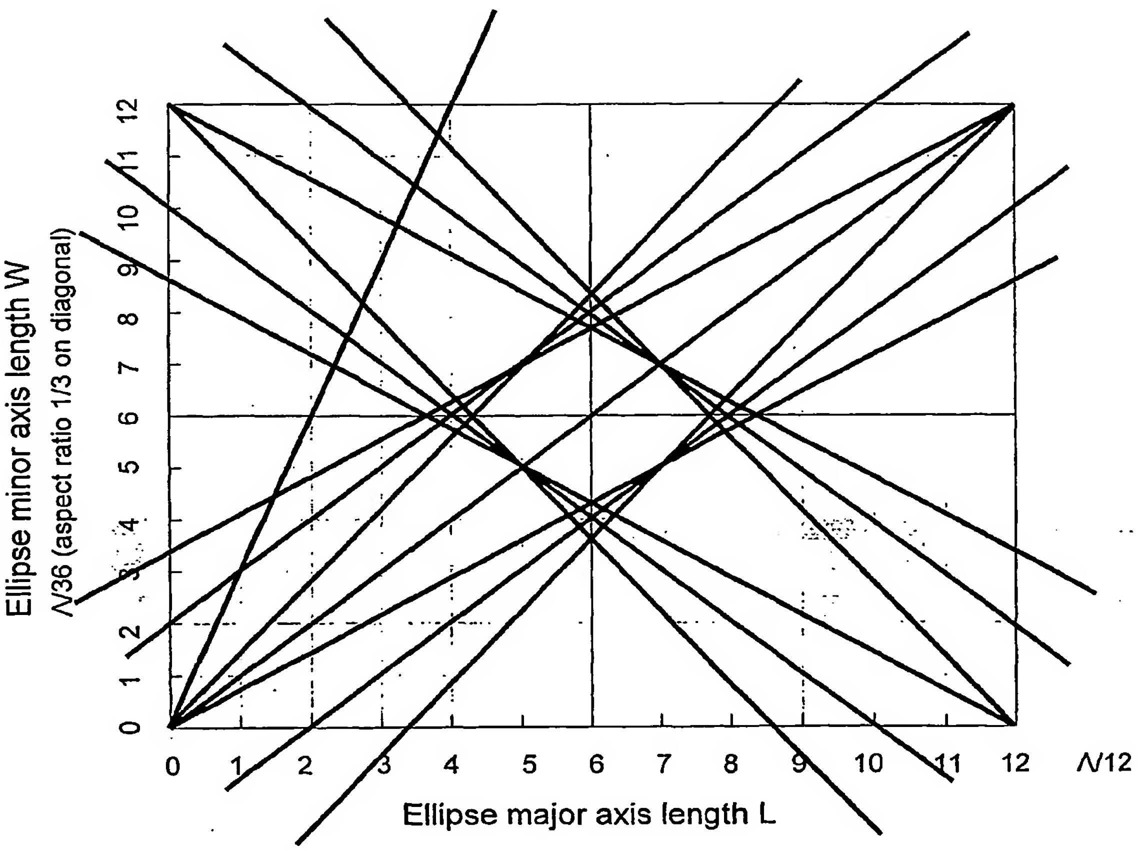

Ellipse minor axis length W
Λ/36 (aspect ratio 1/3 on diagonal)
0
1
2
3
4
5
6
7
8
9
10
11
12
Λ/12
Ellipse major axis length L

Figure 10(a)

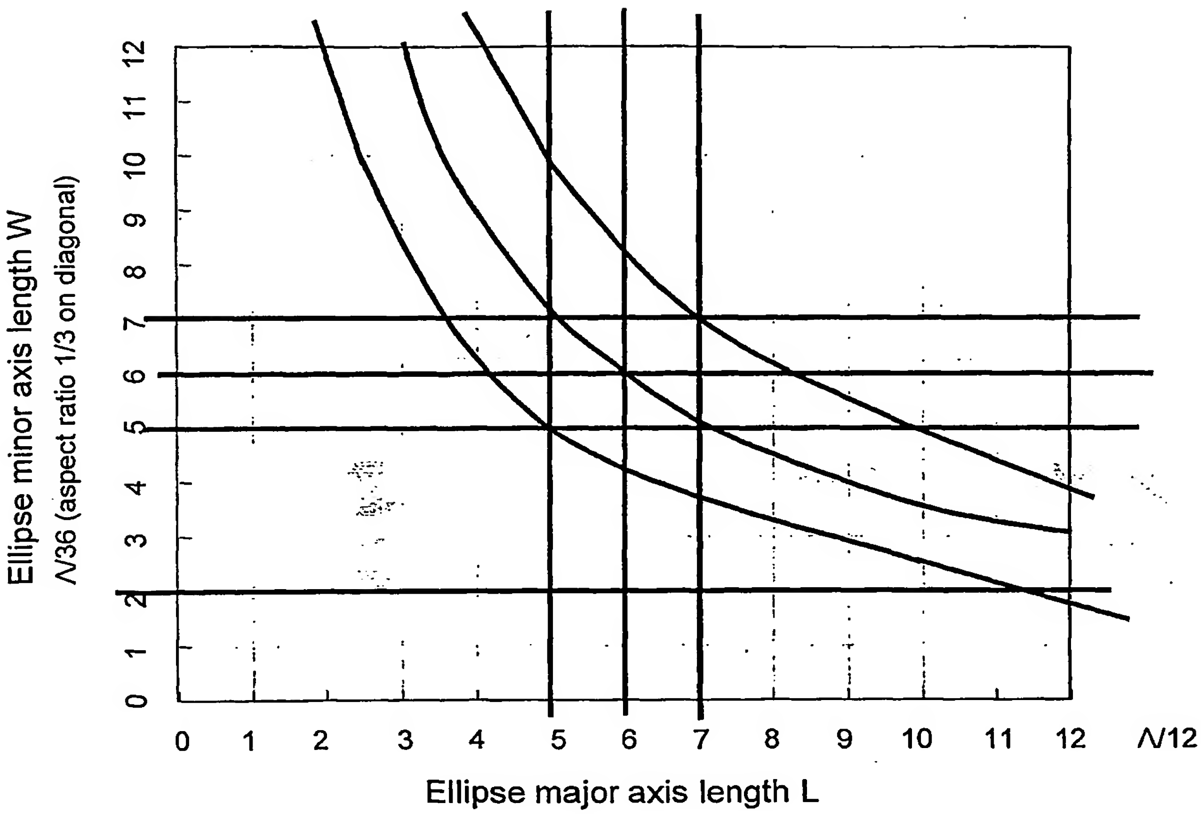

Ellipse minor axis length W
Λ/36 (aspect ratio 1/3 on diagonal)
0
1
2
3
4
5
6
7
8
9
10
11
12
0 1 2 3 4 5 6 7 8 9 10 11 12 Λ/12
Ellipse major axis length L

Figure 10(b)

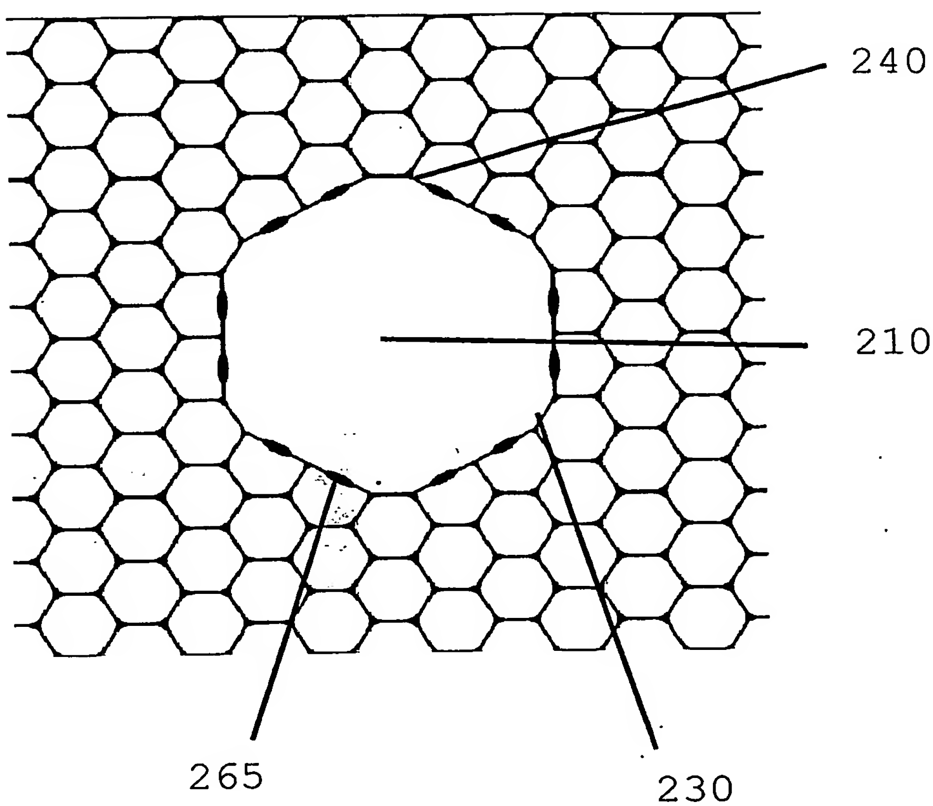


Figure 11

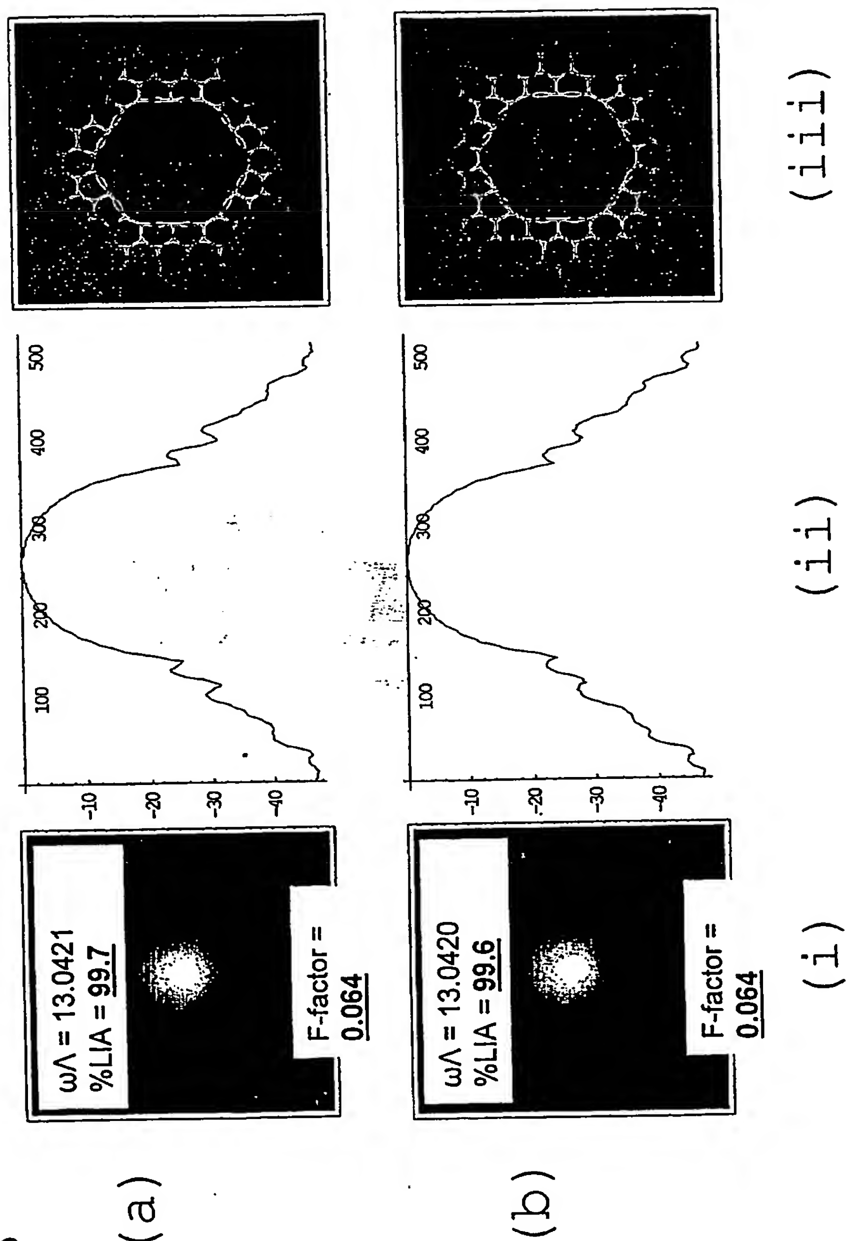

ωΛ = 13.0421
%LIA = 99.7
F-factor =
0.064
ωΛ = 13.0420
%LIA = 99.6
F-factor =
0.064
-10
-20
-30
-40
100
200
300
400
500
(a)
(b)
(i)
(ii)
(iii)

Figure 12

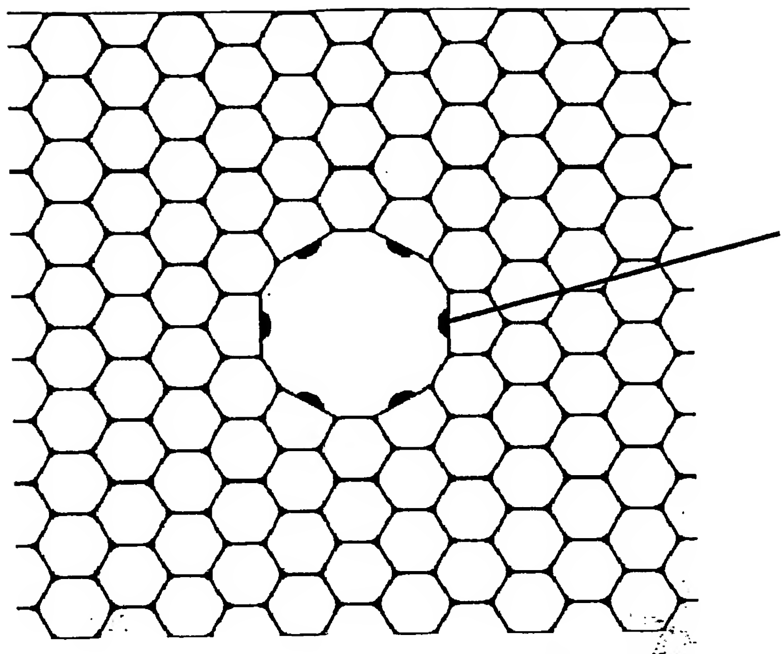


Figure 13

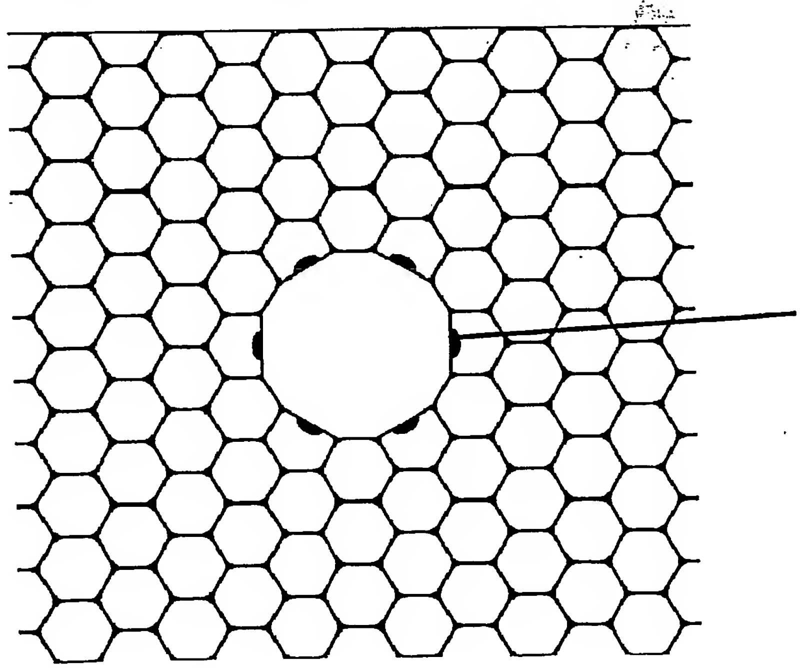


Figure 14

Figure 15

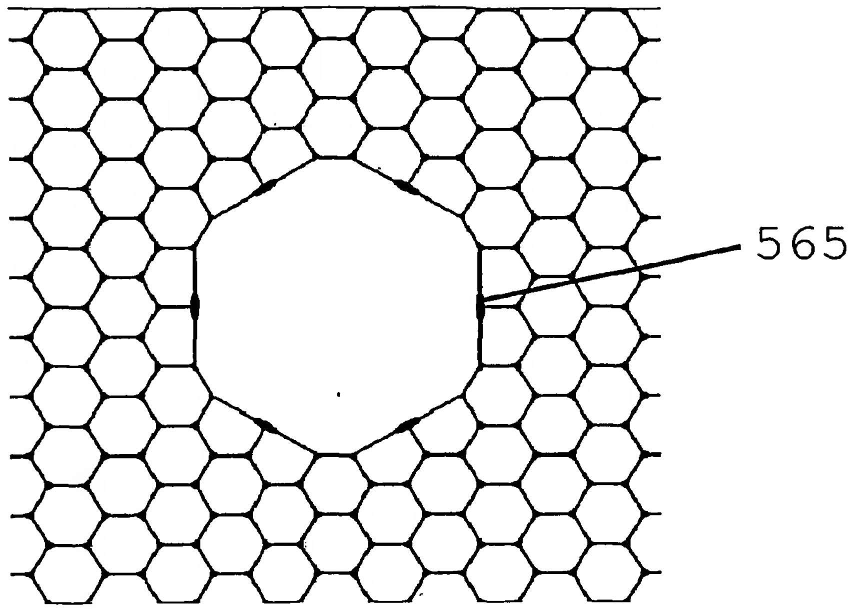
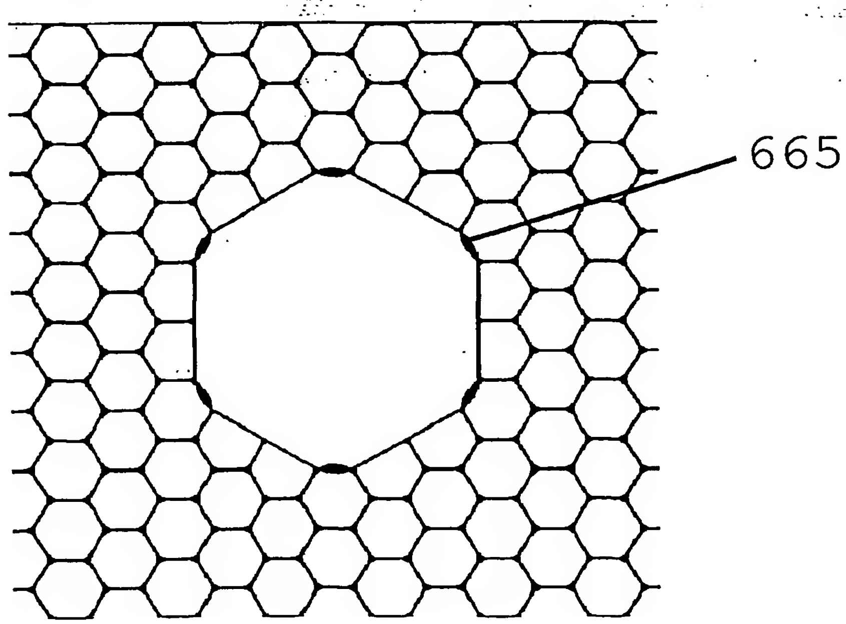


Figure 16



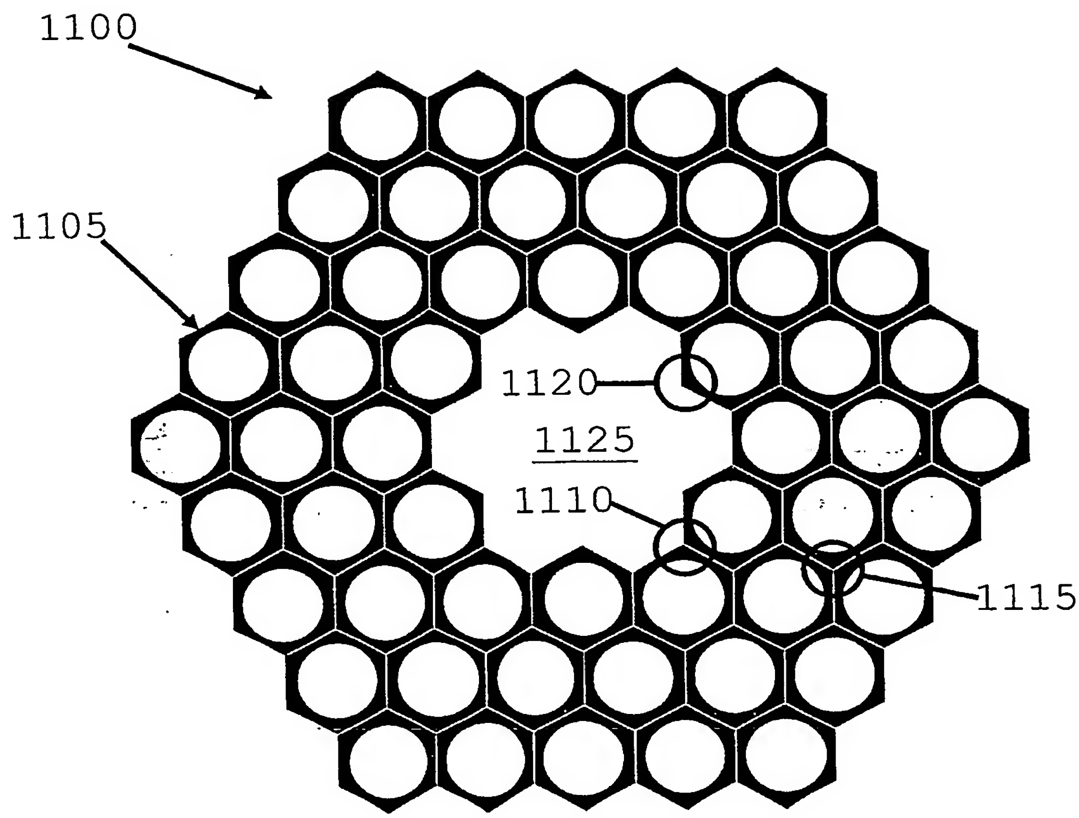


Figure 17

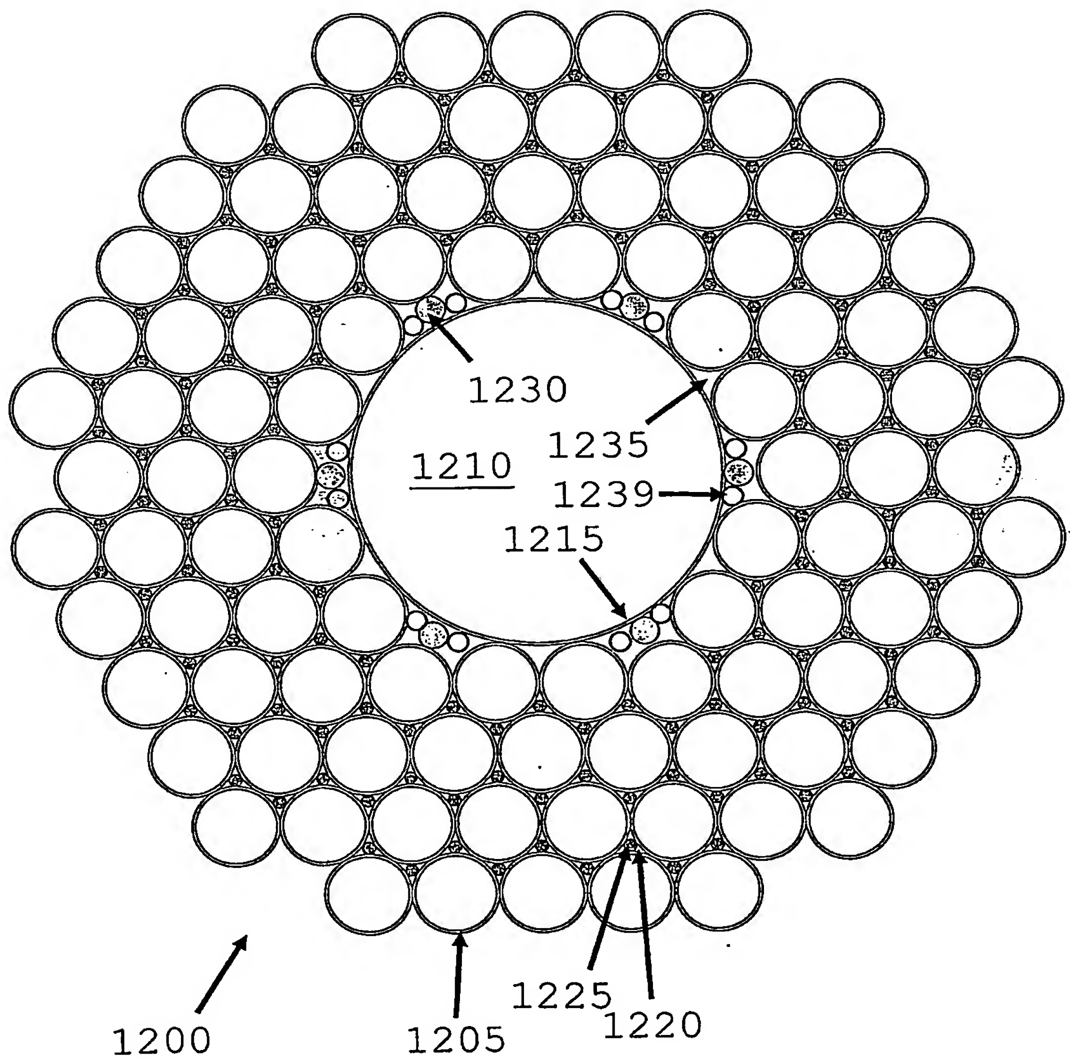


Figure 18

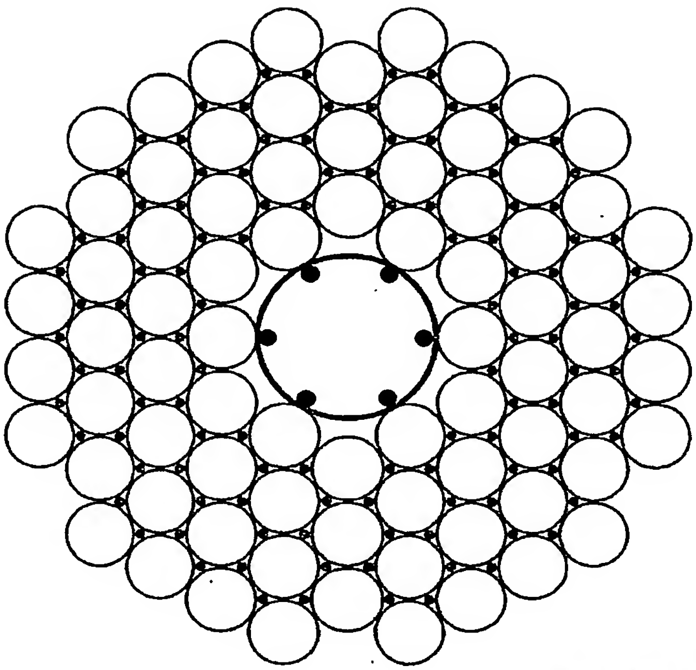


Figure 19a

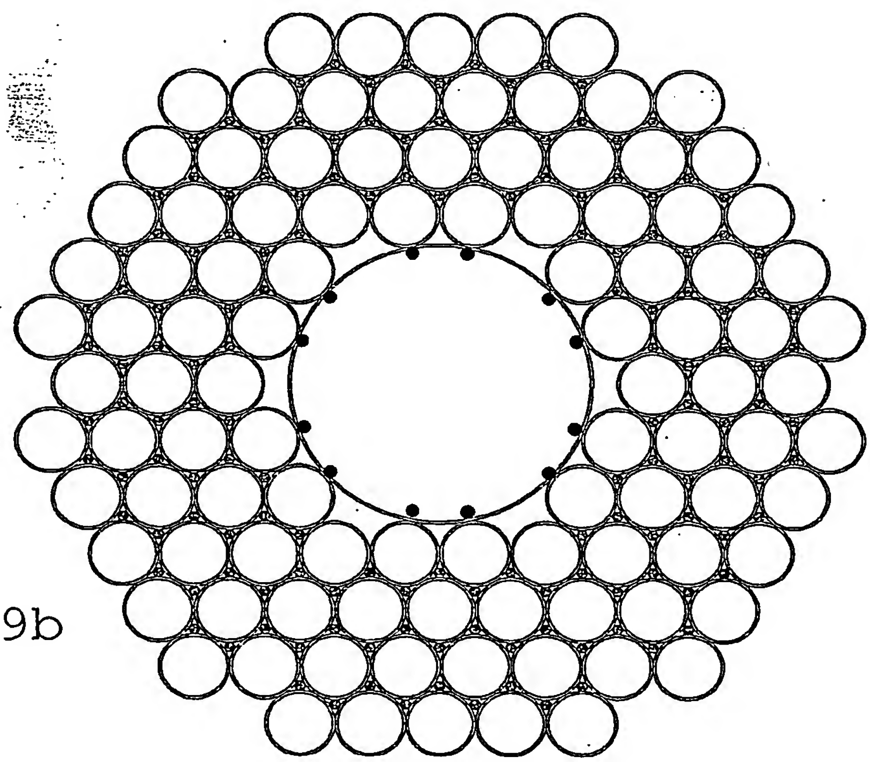


Figure 19b

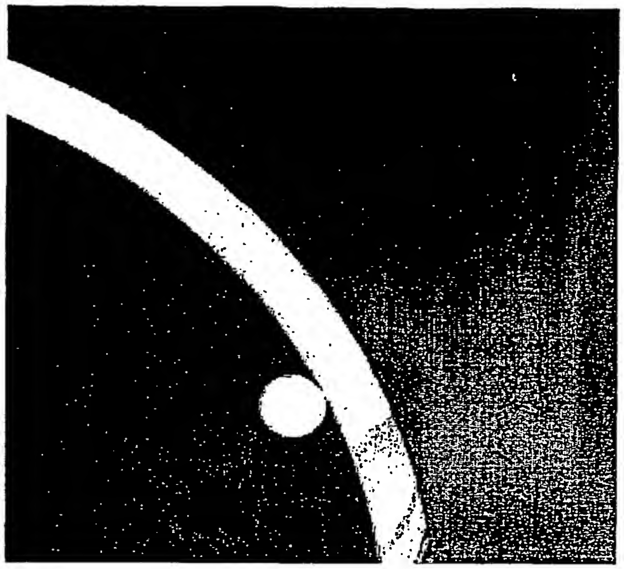


Figure 20a

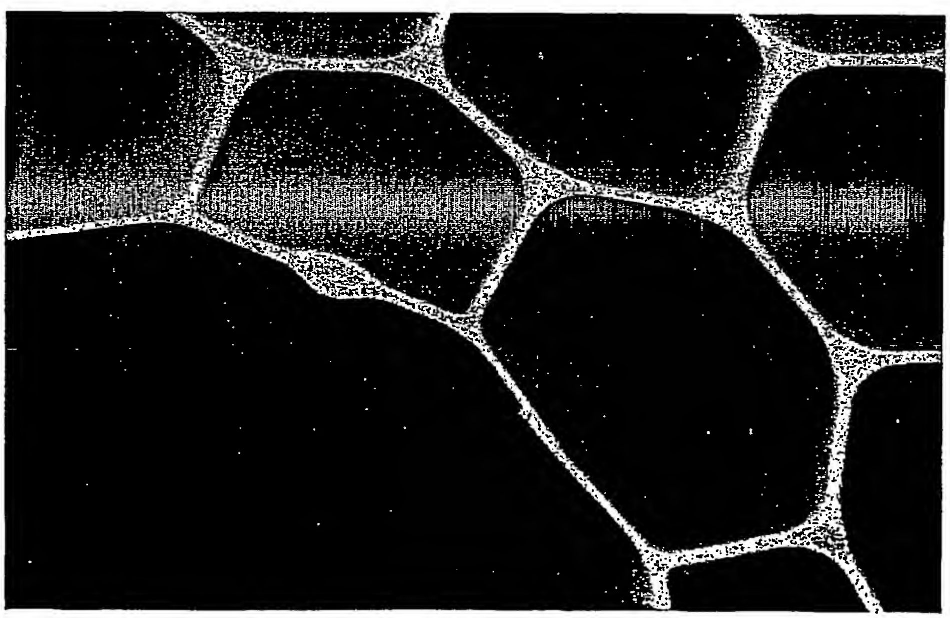


Figure 20b

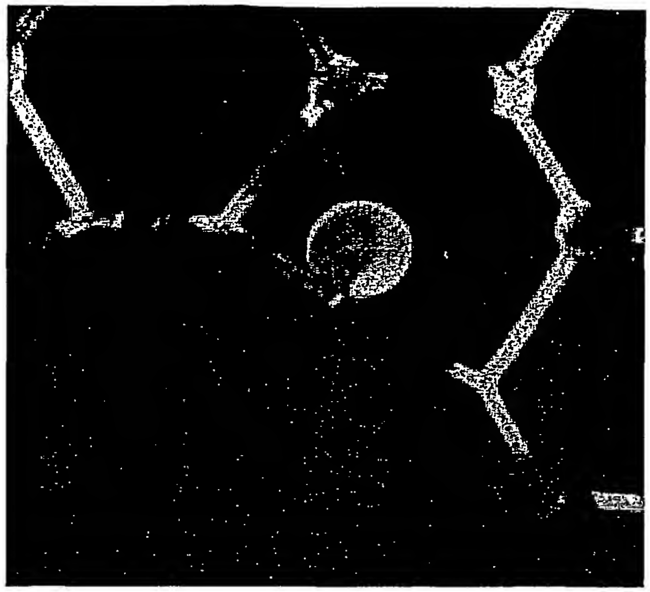


Figure 21a

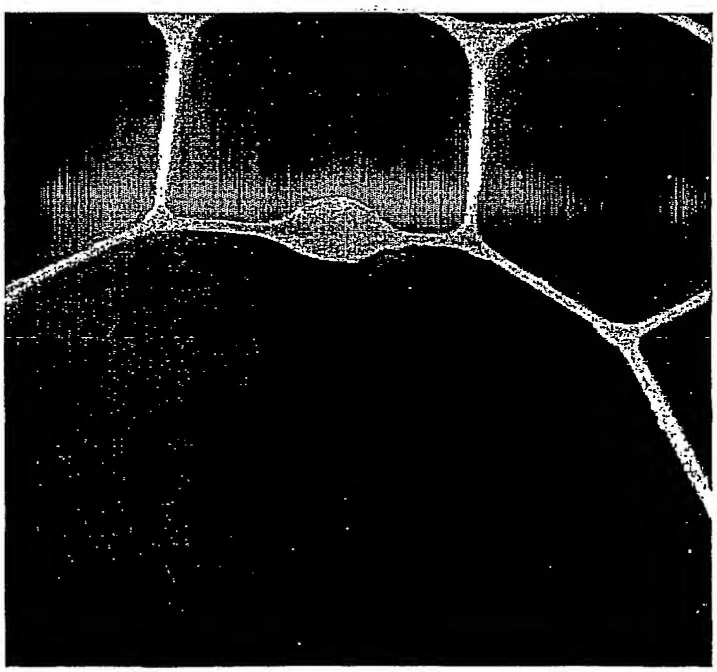


Figure 21b

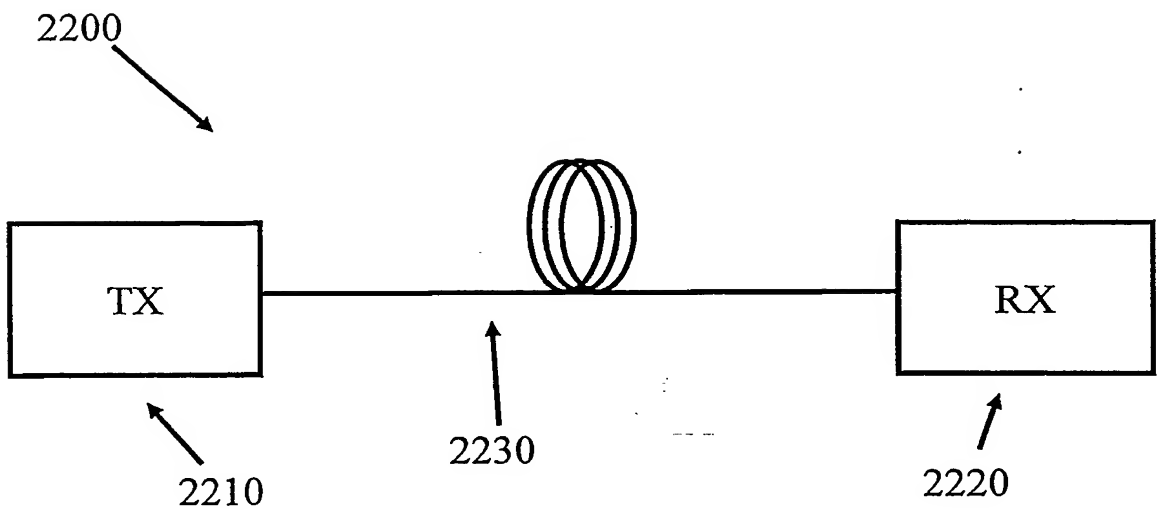


Figure 22

INTERNATIONAL SEARCH REPORT

PCT/GB2004/001288

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 02/075392 A (CORNING INC) 26 September 2002 (2002-09-26) cited in the application	1-12,14, 17-22, 26,29, 42-45, 47,48, 50-53,55
	page 5, line 23 - line 32; figures 10,11	
Y	page 11, line 15 - page 12, line 30	13,15, 16, 23-25, 27,28, 30,31, 49,57,59

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 July 2004	05/08/2004

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Bourhis, J-F

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	VENKATARAMAN N ET AL: "LOW LOSS (13 dB/km) AIR CORE PHOTONIC BAND-GAP FIBRE" ECOC 2002. 28TH. EUROPEAN CONFERENCE ON OPTICAL COMMUNICATION. POST-DEADLINE PAPERS. COPENHAGEN, DENMARK, SEPT. 8 - 12, 2002, EUROPEAN CONFERENCE ON OPTICAL COMMUNICATION.(ECOC), vol. CONF. 28, 12 September 2002 (2002-09-12), page PD11, XP001158363 cited in the application page PD1.1	60
Y	figure 1	13,15, 16, 23-25, 27,28, 30,31,49
Y	KNIGHT J C ET AL: "PHOTONIC BAND GAP GUIDANCE IN OPTICAL FIBERS" SCIENCE, AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE,, US, vol. 282, no. 5393, 20 November 1998 (1998-11-20), pages 1476-1478, XP001009986 ISSN: 0036-8075 the whole document	57
X	LITCHINITSER N M ET AL: "ANTIRESONANT REFLECTING PHOTONIC CRYSTAL OPTICAL WAVEGUIDES" OPTICS LETTERS, OPTICAL SOCIETY OF AMERICA, WASHINGTON, US, vol. 27, no. 18, 15 September 2002 (2002-09-15), pages 1592-1594, XP001161774 ISSN: 0146-9592 cited in the application page 1592	1-5
Y	page 1594; figure 4	59
X	WO 99/64903 A (BARKOU STIG EIGIL ; BJARKLEV ANDERS OVERGAARD (DK); BROENG JES (DK)) 16 December 1999 (1999-12-16) page 9, line 4 - page 25, line 28 figures 4,16-19	1-10, 42-53,55
P,X	WEST J A ET AL: "Photonic band-gap fiber - fiber of the future?" LEOS SUMMER TOPICAL MEETING, 14 July 2003 (2003-07-14), pages 9-10, XP010653076 the whole document	60

-/--

INTERNATIONAL SEARCH REPORT

PCT/GB2004/001288

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	OPTICAL FIBER COMMUNICATIONS 2004, 22 February 2004 (2004-02-22), page PDP24, XP002287920 cited in the application the whole document -----	1-10, 42-45, 47-53,55

INTERNATIONAL SEARCH REPORT

PCT/GB2004/001288

Box II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.: 54
because they relate to subject matter not required to be searched by this Authority, namely:

the subject matter of claim 54 relates to presentation of information, which the International Sarching Authority is not required to search, in application of Article 17(2)(a) PCT and rule 39.1(v) PCT.

2. [X] Claims Nos.: 32-41,56,58,61
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

see FURTHER INFORMATION sheet PCT/ISA/210

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest.

[ ] No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.1

Claims Nos.: 54

the subject matter of claim 54 relates to presentation of information, which the International Sarching Authority is not required to search, in application of Article 17(2)(a) PCT and rule 39.1(v) PCT.

Continuation of Box II.2

Claims Nos.: 32-41,56,58,61

Inequalities in present claims 32-41 are not clear as L , the nodule length, appears as a dimensionless number and no unit is given, rendering comparison with prior art meaningless. The description does not contain any further information on the way to interpret those inequalities.

Present Claims 56,58 do not meet the requirements of support by description of Article 6 PCT because their subject-matter includes a photonic bandgap structure in the core, which is not supported by the description.

Present claim 61 which relies on references to drawings of the present application is not allowable under Rule 6.2.(a) PCT. It is not clear which elements of the drawings have to be considered as technical features.

Such a lack of clarity renders a meaningful search of the claims 32-41, 56, 58 and 61 impossible.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.5), should the problems which led to the Article 17(2) declaration be overcome.

INTERNATIONAL SEARCH REPORT

PCT/GB2004/001288

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 02075392 A	26-09-2002	EP 1370893 A2	17-12-2003
		TW 539875 B	01-07-2003
		WO 02075392 A2	26-09-2002
		US 2002136516 A1	26-09-2002
		US 2004105645 A1	03-06-2004
WO 9964903 A	16-12-1999	AT 268482 T	15-06-2004
		AT 266214 T	15-05-2004
		AU 755223 B2	05-12-2002
		AU 3026099 A	30-12-1999
		AU 755547 B2	12-12-2002
		AU 3810699 A	30-12-1999
		CA 2334510 A1	16-12-1999
		CA 2334554 A1	16-12-1999
		DE 69917022 D1	09-06-2004
		DE 69917776 D1	08-07-2004
		WO 9964904 A1	16-12-1999
		WO 9964903 A1	16-12-1999
		EP 1086393 A1	28-03-2001
		EP 1086391 A1	28-03-2001
		JP 2002517793 T	18-06-2002
		JP 2002517794 T	18-06-2002
		NZ 509201 A	26-11-2002
		US 6539155 B1	25-03-2003